REPORT #
RRTAC 89-2

Proceedings of the Conference "Reclamation, A Global Perspective"

Calgary, Alberta
August 27 - 31, 1989
Volume II

Heritage Fund

Alberta

LAND CONSERVATION AND
RECLAMATION COUNCIL
Reclamation Research
Technical Advisory Committee

Alberta's Reclamation Research Program

Regulating surface disturbances in Alberta is the responsibility of the Land Conservation and Reclamation Council. The Council executive consists of a Chairman from Alberta Environment and two deputy chairmen from Alberta Forestry, Lands and Wildlife. The Council oversees a reclamation research program, established in 1978, to identify the most efficient methods for achieving acceptable reclamation in the province. Funding for the research program is provided by Alberta's Heritage Savings Trust Fund, Land Reclamation Program.

To assist with development and administration of the research program, the Council appointed the interdepartmental Reclamation Research Technical Advisory Committee (RRTAC). The Committee consists of eight members representing the Alberta Departments of Agriculture, Energy, Forestry, Lands and Wildlife, and Environment, and the Alberta Research Council. The Committee updates research priorities, reviews research proposals, organizes workshops, and otherwise acts as the coordinating body for reclamation research in Alberta.

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August 27-31, 1989

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Association Canadienne de Réhabilitation des Sites Degradés

and the

American Society for Surface Mining and Reclamation

Compiled by

D.G. Walker, C.B. Powter, and M.W. Pole

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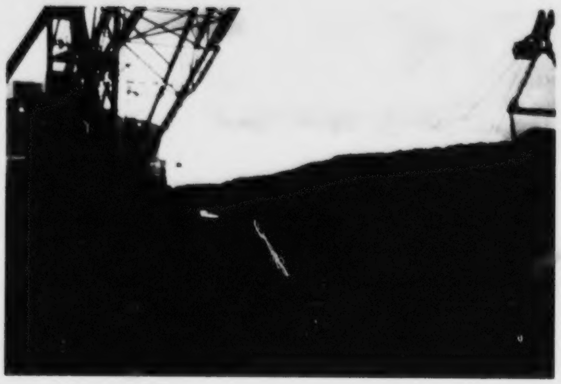

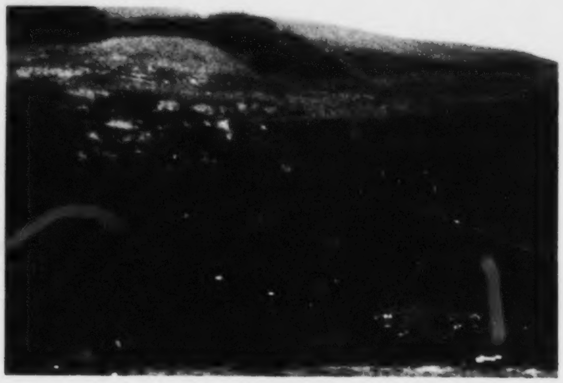

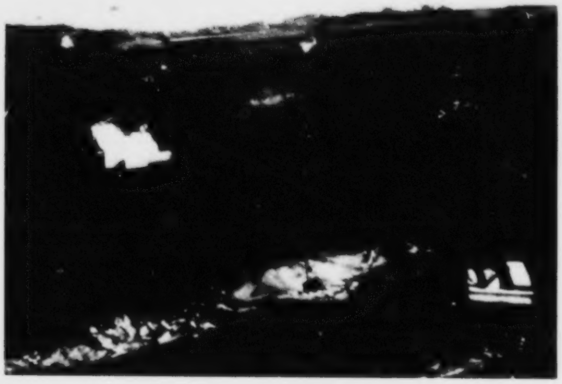

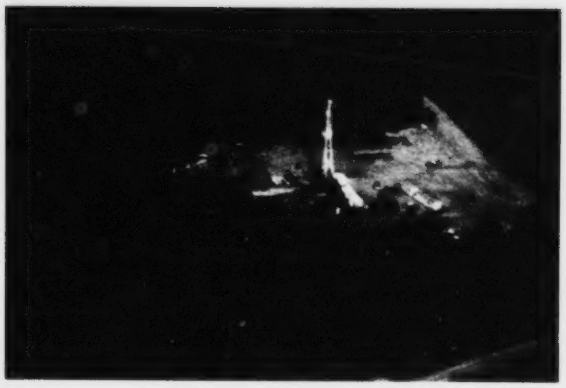

Mission: To coordinate and foster reclamation research in Alberta.

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Disclaimer

The papers contained in this proceedings were peer-reviewed and comments provided to the authors. However, it was the final responsibility of the authors to address these comments.

The content, recommendations and conclusions in this report are therefore those of the authors and not of the Alberta Government or its representatives.

This report is intended to provide government and industry staff with up-to-date technical information to assist in the preparation and review of Development and Reclamation Approvals, and development of guidelines and operating procedures. This report is also available to the public so that interested individuals similarly have access to the most current information on land reclamation topics.

Acknowledgements

This conference was jointly organized by the Canadian Land Reclamation Association/Association Canadienne de Réhabilitation des Sites Degradés and the American Society for Surface Mining and Reclamation. The following members of these organizations were particularly helpful: Stu Bengson, Richard Barth, Daniel Boivin, Jon Burley, Kent Crofts, Al Fedkenheuer, Gail Harrison, Darlene Hergott, Al Kennedy, Tom Oddie, Les Panek, Bill Plass, Mike Pole, Chris Powter, Holly Quan, Ron Ries and David Walker. Mr. Marc St.-Onges provided the French translations for the Abstracts. The success of the conference was also due to the efforts of several people who helped out on the registration desk and with the audio/visual systems.

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A special note of thanks to the Reclamation Research Technical Advisory Committee of the Alberta Land Conservation and Reclamation Council for publishing these proceedings.

Finally, but perhaps most importantly, the following page lists the organizations that sponsored the conference, either in the form of a direct financial contribution, or through the donation of time, supplies or services for the organizers to complete their tasks. The support of these organizations is greatly appreciated.

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Problems and Solutions

Session Chairmen: W.E. Dodd and J.C. Chambers

TAILINGS DISPOSAL SYSTEM AT TROMBETAS BAUXITE MINE[1]

by

Reginaldo P. Lapa and Fernando V. Carreresi[2]

Abstract. Mineracao Rio do Norte (MRN) started its bauxite washing operation in 1979. Since then, the tailings have been dumped into nearby Batata Lake. The annual tailings volume is about 18 million m^3 at a solids content of 7-9%. This has caused a serious ecological problem. Early in the operation MRN and the environmental protection authorities decided that a more ecologically acceptable method for tailings disposal should be investigated.

In 1982, the consultants, Bromwell and Carrier Inc., (Lakeland, Florida) started thickening and pumping tests on the tailings deposited in Batata Lake. Pilot tests in a small settling pond were commenced in 1984. As a result of the tests, it was proposed to deposit the thickened tailings in the mined out areas. This will be an innovative method not only in Brazil but also on the worldwide bauxite mining scene.

This paper describes the mining method, industrial facilities, the studies on thickening and pumping, the studies for disposal of the tailings in the mined out areas, the tailings disposal plan and finally the reclamation of the disposal areas.

Introduction

Mineracao Rio do Norte was created in 1967 to operate the Trombetas bauxite mine. The shareholders are Companhia Vale do Rio Doce (46%), Alcan (24%), Companhia Brasileira de Aluminio (10%), Norks Hydro (5%), and Reynolds Aluminum (5%).

The mining operations are located in the Amazon region, Para State, on the right bank of the Trombetas River. This river is a tributary of the Amazon, joining it from the north, at about 800 km from the mouth of the Amazon (Figure 1).

The beneficiation operations are presently situated at Porto Trombetas. Facilities also include the shiploader, offices, shops, warehouses, and power plant. Around Porto Trombetas there is a complete mine town with hospital, supermarket, school, and recreational facilities.

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[1] Paper presented at the conference Reclamation, A Global Perspective, held in Calgary, Alberta, Canada, August 27-31, 1989.

[2] Mining Manager and Production Superintendent, respectively, Mineracao Rio do Norte S.A., Porto Trombetas, Para, Brazil, 68275

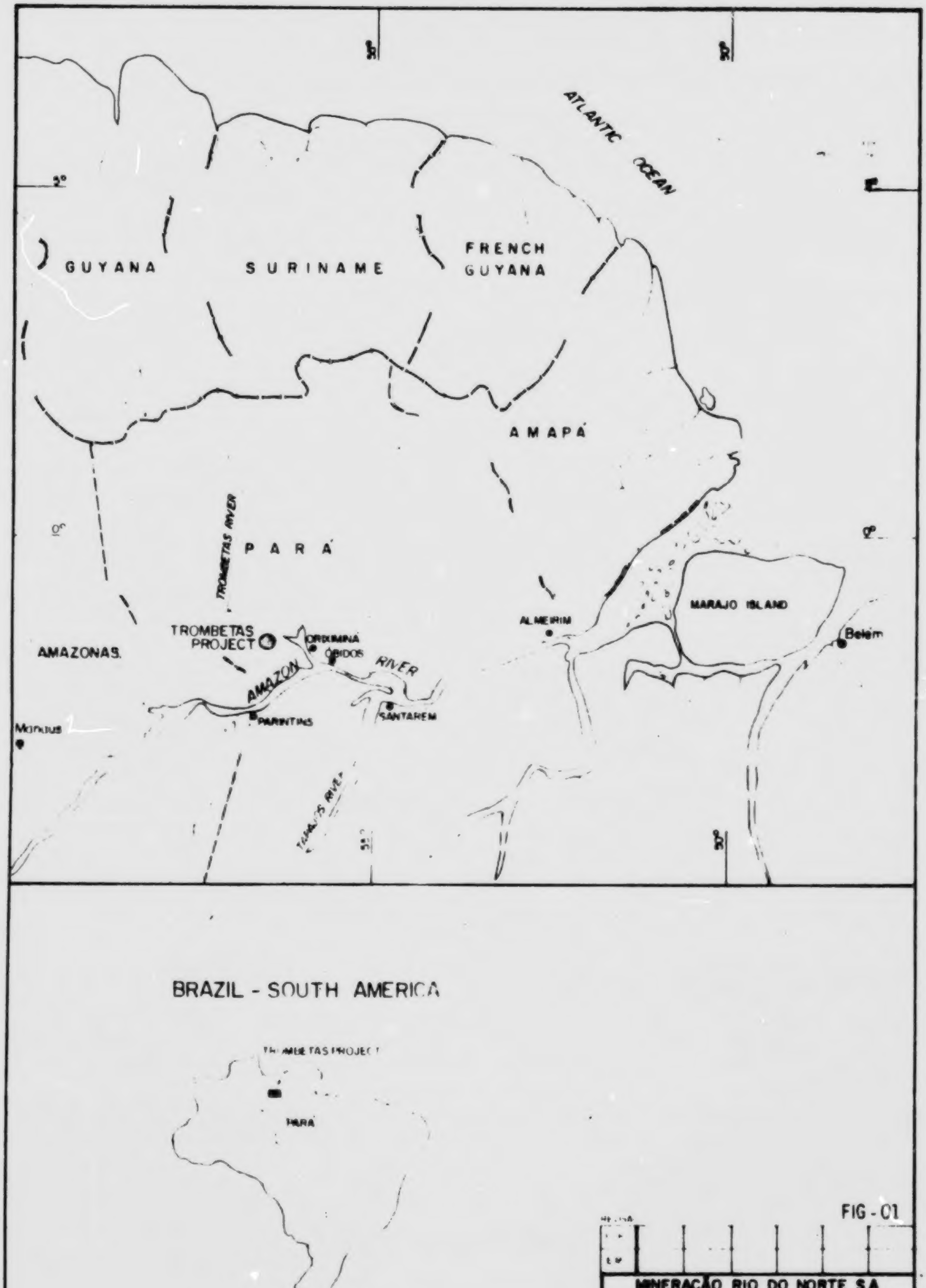
ATLANTIC OCEAN
2°
GUYANA
SURINAME
FRENCH GUYANA
AMAPÁ
TROMBETAS RIVER
PARÁ
0°
AMAZONAS
TROMBETAS PROJECT
ORIXIMINA
ÓBIDOS
AMAZON RIVER
PARINTINS
SANTAREM
Manaus
ALMEIRIM
MARAJO ISLAND
Belém
TAPAJÓS RIVER
55°
50°
BRAZIL - SOUTH AMERICA
TROMBETAS PROJECT
PARÁ

FIG - 01

MINERAÇÃO RIO DO NORTE S.A
TROMBETAS PROJECT

LOCATION MAP

JUL /87

The Trombetas bauxite project started operations in 1979. The rated annual capacity was 3.35 million tonnes of product. Several improvements raised the production capacity to 5.0 million tonnes/year. The main users of the Trombetas bauxite at present are Brazil (36%), Venezuela (33%), Canada (26%), USA (2%), UK (2%), and West Germany (1%).

Geology

The Trombetas bauxite occurs on extensive plateaux with elevations between 50 and 200 meters. The typical profile (Figure 2) shows a tall dense vegetation overlying a thin (0.50 m) soil. Below the soil is a yellow kaolinitic clay whose thickness can reach 11 meters. The clay overburden passes to nodular bauxite, up to 2.5 meters thick, consisting of ferruginous pisolites and gibbsite nodules in a clay matrix. The nodular bauxite is presently being treated as waste, although studies are being carried out aimed at recovering this bauxite. The next layer is the ferruginous laterite which averages 2 meters in thickness. The succession described above represents the overburden that overlies the massive bauxite layer which reaches a thickness of 7 meters.

Trombetas massive bauxite is essentially gibbsitic (thihydrate) containing less than 1% boehmite (monohydrate). The main minerals are gibbsite, kaolinite, hematite and goethite. The top of the bauxite layer is harder than the rest, reflecting a higher iron content. The middle and bottom sections of the layer show variable texture: granular, friable, and porous. Closer to the base of the horizon, there are blocks of bauxite disseminated in a clay matrix resulting in an irregular contact. Vertical pipes of kaolinitic clay penetrate the basal portion of the massive bauxite. This clay and the irregular contact result in a dilution of the ore grade.

The reserves of massive bauxite of MRN are roughly 500 million tonnes on a washed basis. The average grade is 50.24% available alumina (av.Al_2O_3), 4.25% reactive silica (re.SiO_2), and 9.66% iron oxide (Fe_2O_3). The ore bodies occur on several plateaux in the area (Figure 3).

The average recovery at the washing plant is 74% by weight. The remaining 26% represents the tailings that are mainly clay.

Mining

Present mining operations are being carried out in the Saraca I concession (see Figure 3). Here the ore body covers some 232 ha.

The mining method is similar to the strip mining used in surface coal mines. The mining cuts are 28 m wide and 600 to 1000 m long. The mining stages are: clearing the forest, stripping, drilling and blasting, excavation and loading, hauling, and finally the rehabilitation of the mined out areas (Figure 4).

CAT D8L tractors fitted with adequate protection equipment fell the tress, and the wood with no commercial value is burned. In the stripping operation two diesel draglines (BE-480W) with 17 cubic yard buckets, one electric dragline (BE-60W) with a 26 cubic yard bucket and a motorscraper fleet are used. Three electro-hydraulic Liebherr back-hoes with 8.3 m^3 buckets excavate the bauxite.

Only the top half of the bauxite layer is hard enough to require blasting. Blastholes are drilled by 6 inch augerdrills mounted on trucks. The explosive is ammonium nitrate

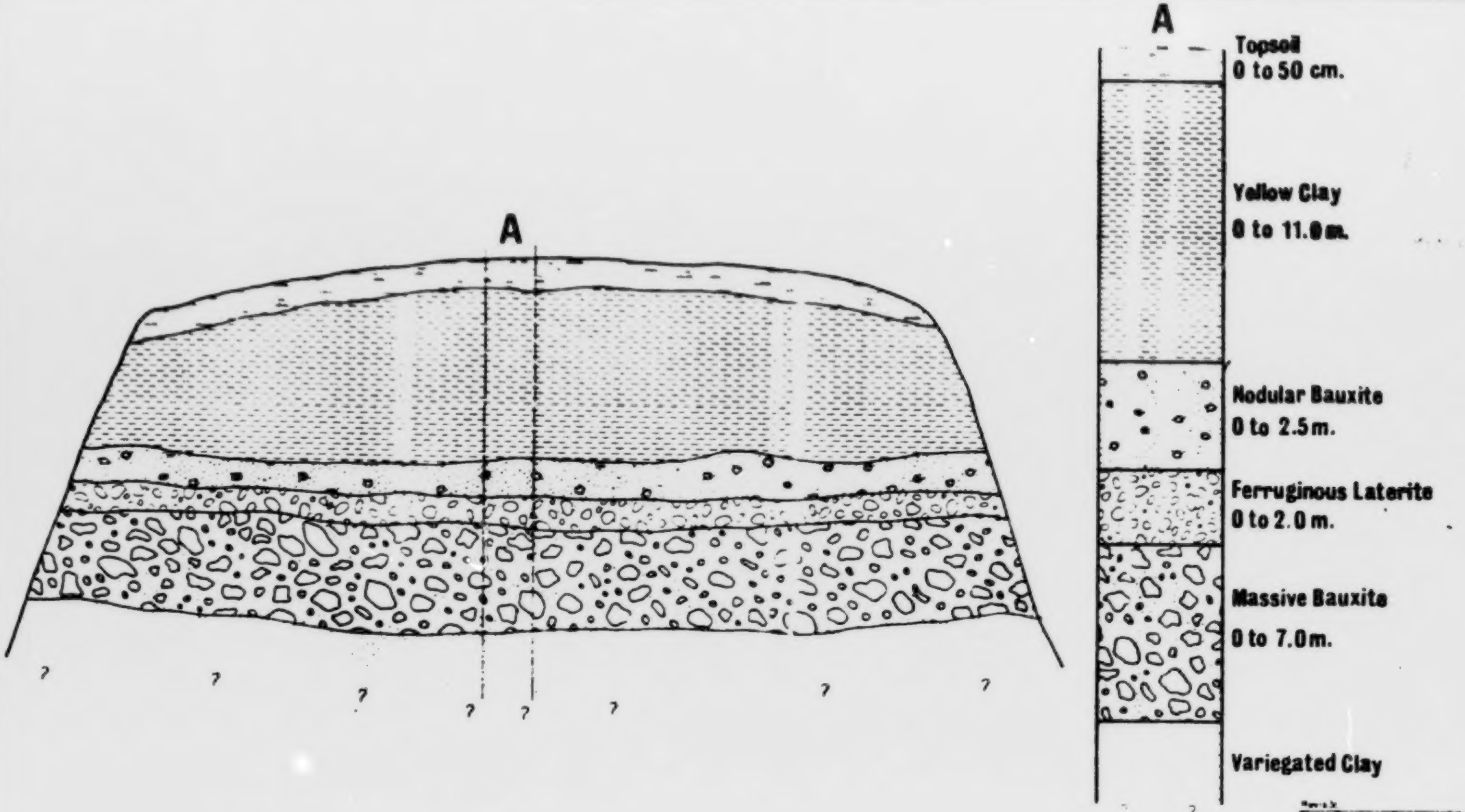
A
A
Topsoil
0 to 50 cm.
Yellow Clay
0 to 11.0 m.
Nodular Bauxite
0 to 2.5 m.
Ferruginous Laterite
0 to 2.0 m.
Massive Bauxite
0 to 7.0 m.
Variegated Clay
?

FIG-02

MINERAÇÃO RIO DO NORTE S.A.
TROMBETAS PROJECT

TYPICAL SECTION

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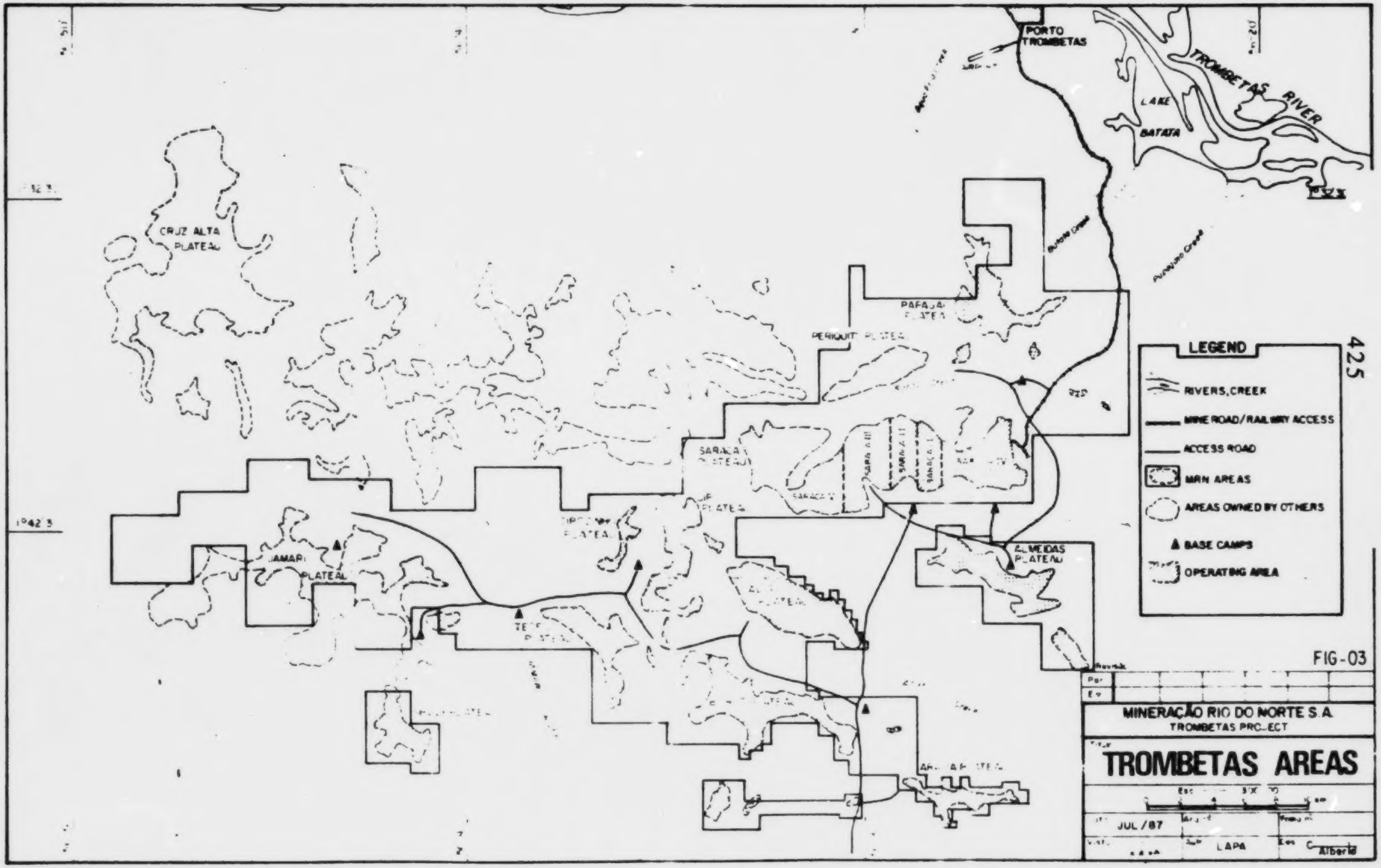
PORTO TROMBETAS
TROMBETAS RIVER
LAKE
BATATA
CRUZ ALTA PLATEAU
PAPAGAIO PLATEAU
PERIQUITO PLATEAU
SARACA PLATEAU
SARACA I
SARACA II
SARACA III
SARACA V
SARACA IV
ALMEIDAS PLATEAU
PLATEAU
JAMARI PLATEAU
TEF PLATEAU
ARAMA PLATEAU
LEGEND
RIVERS, CREEK
MINE ROAD/RAILWAY ACCESS
ACCESS ROAD
MRN AREAS
AREAS OWNED BY OTHERS
▲ BASE CAMPS
OPERATING AREA
1°42'S

FIG-03

MINERAÇÃO RIO DO NORTE S.A
TROMBETAS PROJECT

TROMBETAS AREAS

JUL / 87

LAPA

C. Alberto

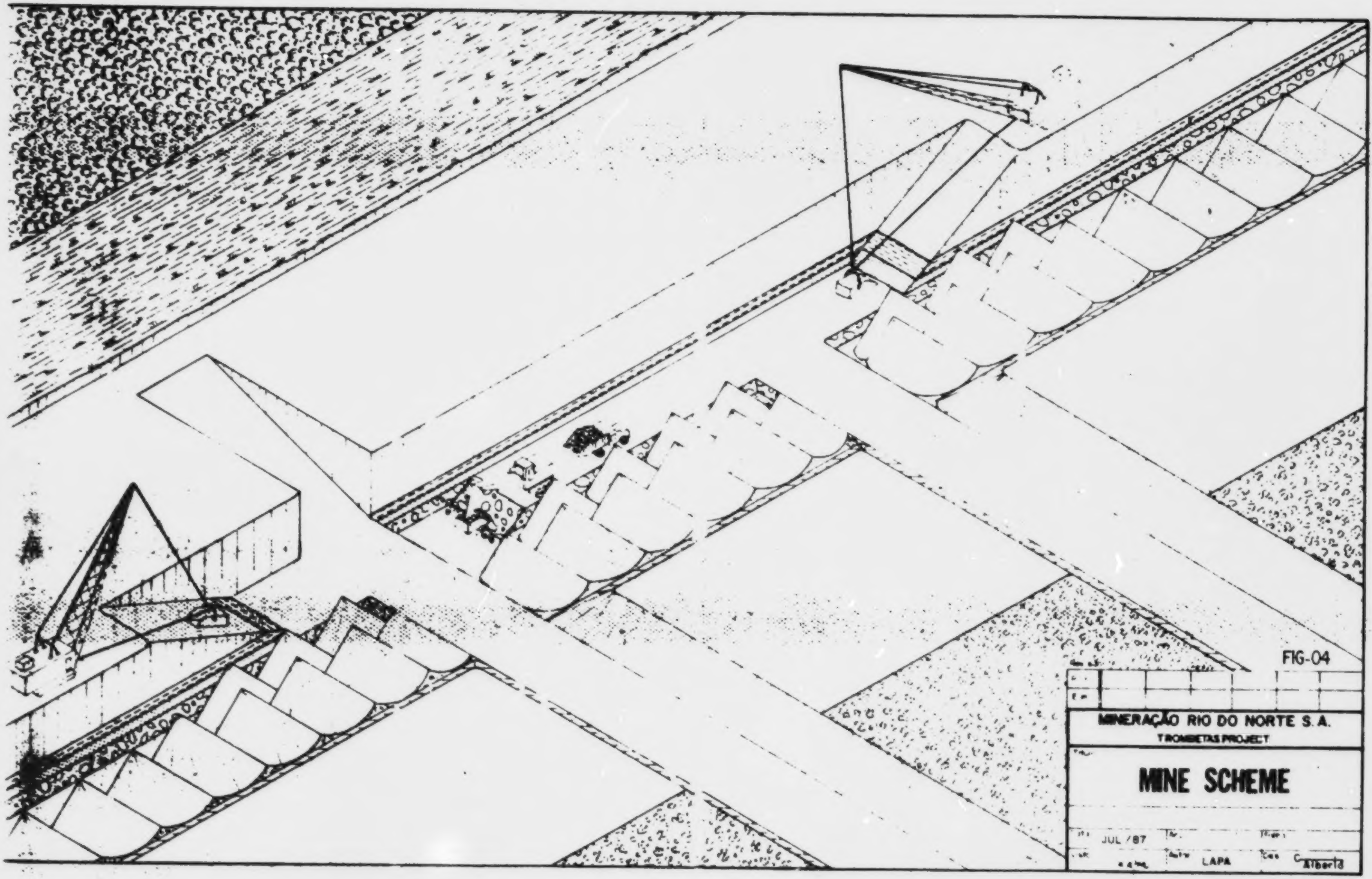
FIG-04
MINERAÇÃO RIO DO NORTE S.A.
TROMBETAS PROJECT
MINE SCHEME
JUL /87
LAPA
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mixed with used engine oil. In the presence of water, an explosive slurry is used. The bauxite is hauled into trucks to the crusher.

When mining is completed, the area is rehabilitated. The piles of spoil left by the draglines are graded, returning the topography roughly to its original form. The topsoil is spread, and finally the mined out areas are revegetated using native tree species.

Beneficiation

As explained in the geological description, the inclusions of kaolinitic clay in the bauxite layer and the irregular contact with the base clay are the main causes of clay contamination in the bauxite. The clay content of the bauxite is reflected in the levels of available alumina and reactive silica. Therefore the beneficiation process at Trombetas consists of size reduction, washing and classifying. This process washes out clay and the result is a decrease in the reactive silica and an increase in the available alumina content.

After being crushed to 3 inches, the bauxite is loaded in 80 ton railcars to be transported 28 km to the beneficiation plant located at Porto Trombetas.

The beneficiation plant produces four types of bauxite: wet coarse bauxite with 12% moisture, dry coarse bauxite with 5% moisture, fine bauxite with 15% moisture, and a superfine product with 15% moisture (Figure 5).

The tailings, as a result, are less than 400 mesh. The disposal of these fine tailings has been studied with primary emphasis on the protection of the ecology.

In shipping 5 million tonnes/year of bauxite, 1.7 million tonnes of tailings solids are produced. The solids content of the slurry is 7 to 9%.

Tailings

History

Since the start of the operations, the tailings have been discharged into Batata Lake (Figure 7).

These tailings consist of fine solid particles, chemically inert, and water. The particles are composed of aluminum oxide (21%), silicates (48%), and iron oxides. At the beginning the tailings particle size was less than 150 mesh. Since 1986 when the recovery of the fraction less than 150 mesh and greater than 400 mesh began, the tailings particle size has been less than 400 mesh (Figure 6).

The progressive silting of the lake, and the concern about the environment, moved MRN to start basic studies on the tailings for analyzing disposal alternatives.

MRN engaged, in 1982, the services of Bromwell and Carrier Inc. as consultants. In 1984, a series of pilot tests were conducted complementing the laboratory tests.

Field and laboratory tests included determination of density, compressibility, permeability, viscosity, Atterberg limit and pumping tests (Figures 8, 9, and 10).

Study of Alternatives

Based on the test results, several alternatives for disposal of the tailings were studied and had their operating cost and investment evaluated (Figure 11). The solution chosen comprises relocating the washing plant close to the mine and

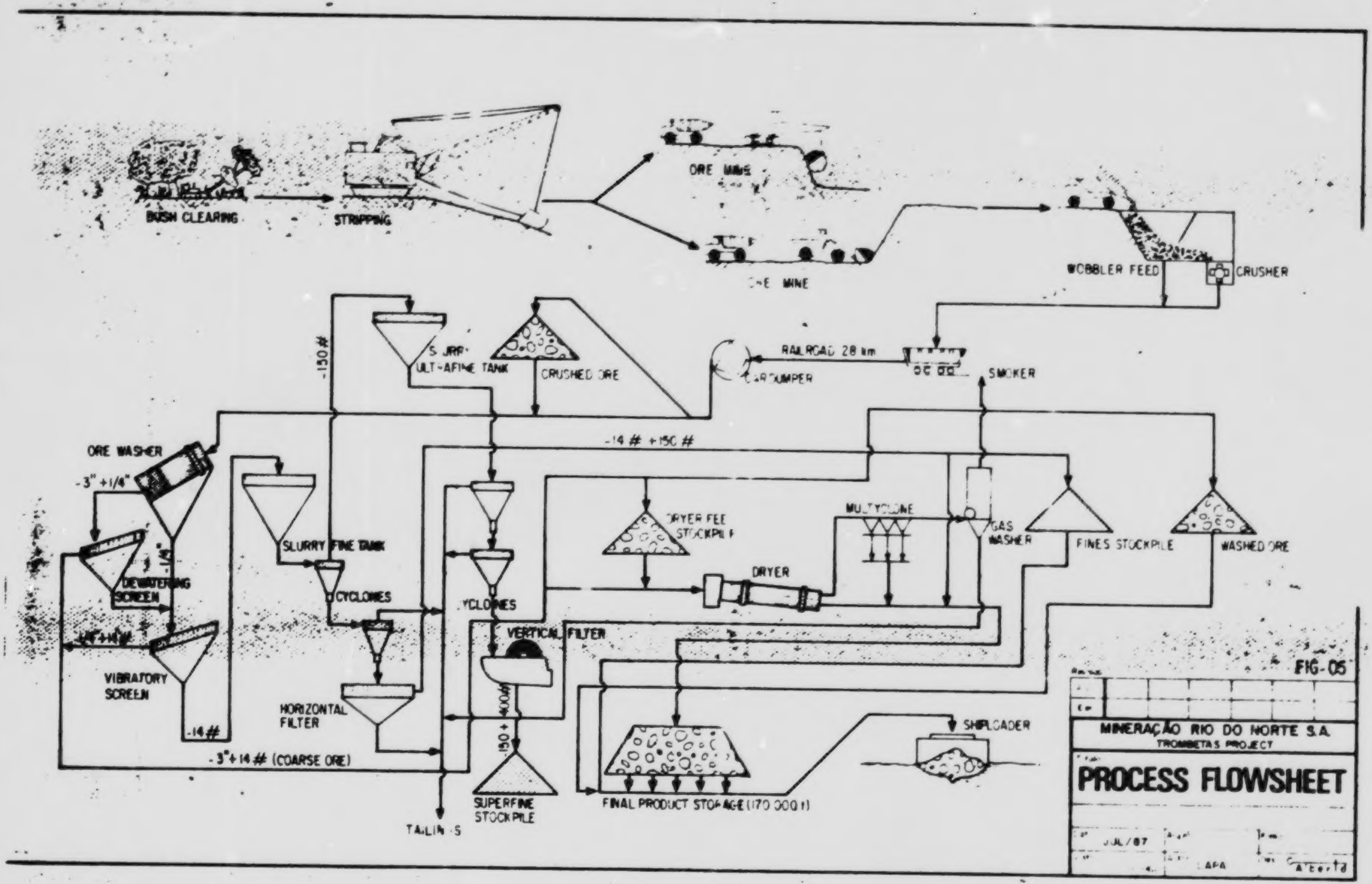

BUSH CLEARING
STRIPPING
ORE MINE
ORE MINE
WOBBLER FEED
CRUSHER
RAILROAD 28 km
CAR DUMPER
SMOKER
SLURRY ULTRAFINE TANK
CRUSHED ORE
-150 #
ORE WASHER
-3" +1/4"
DEWATERING SCREEN
-1/4" +14 #
VIBRATORY SCREEN
-14 #
-3" + 14 # (COARSE ORE)
SLURRY FINE TANK
CYCLONES
HORIZONTAL FILTER
CYCLONES
VERTICAL FILTER
-150 + 400 #
SUPERFINE STOCKPILE
TAILINGS
-14 # +150 #
DRYER FEED STOCKPILE
DRYER
MULTYCLONE
GAS WASHER
FINES STOCKPILE
WASHED ORE
FINAL PRODUCT STORAGE (170 000 t)
SHIPLOADER

FIG-05

MINERAÇÃO RIO DO NORTE S.A.
TROMBETAS PROJECT

PROCESS FLOWSHEET

JUL/87

LAPA

Alberto

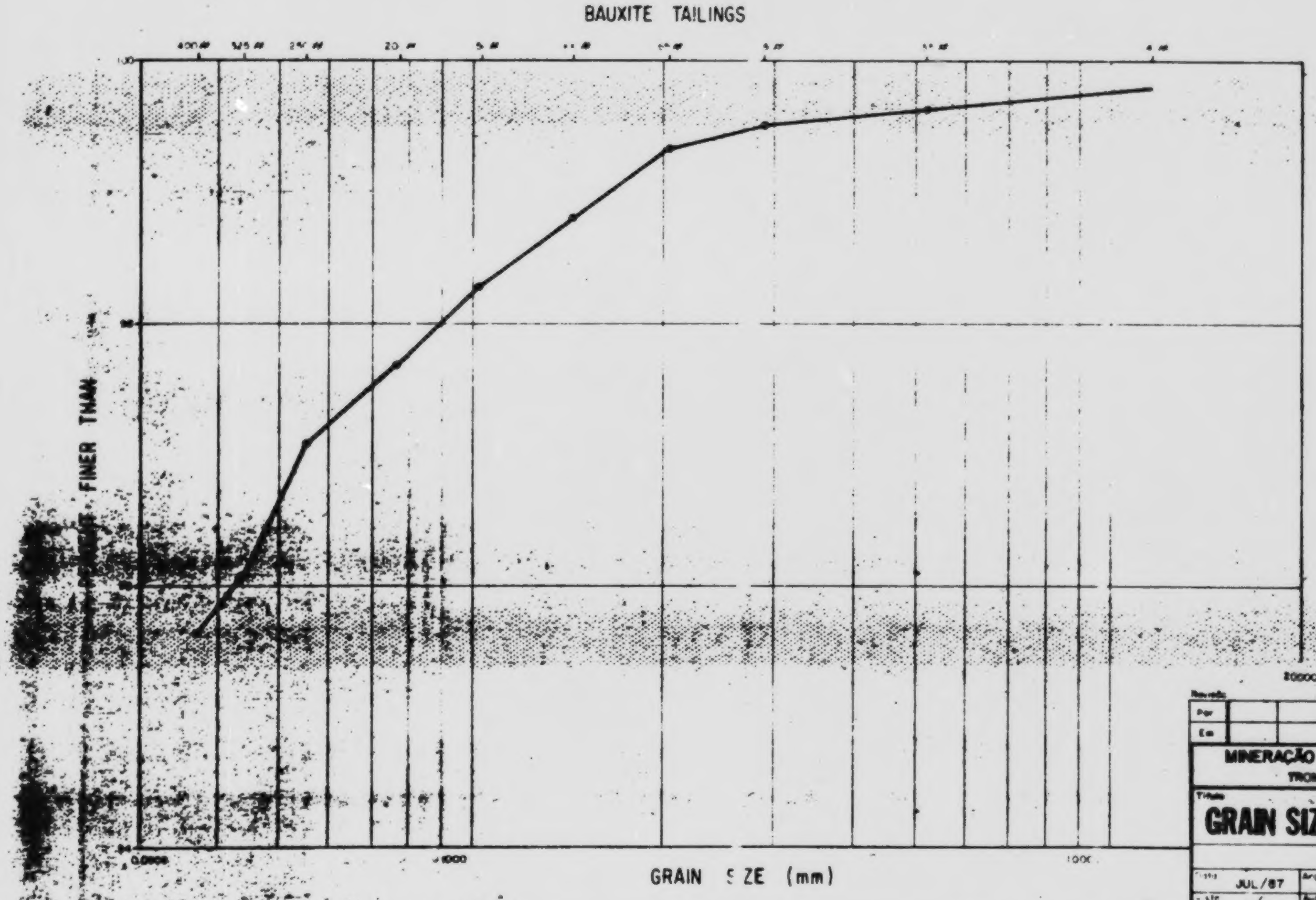


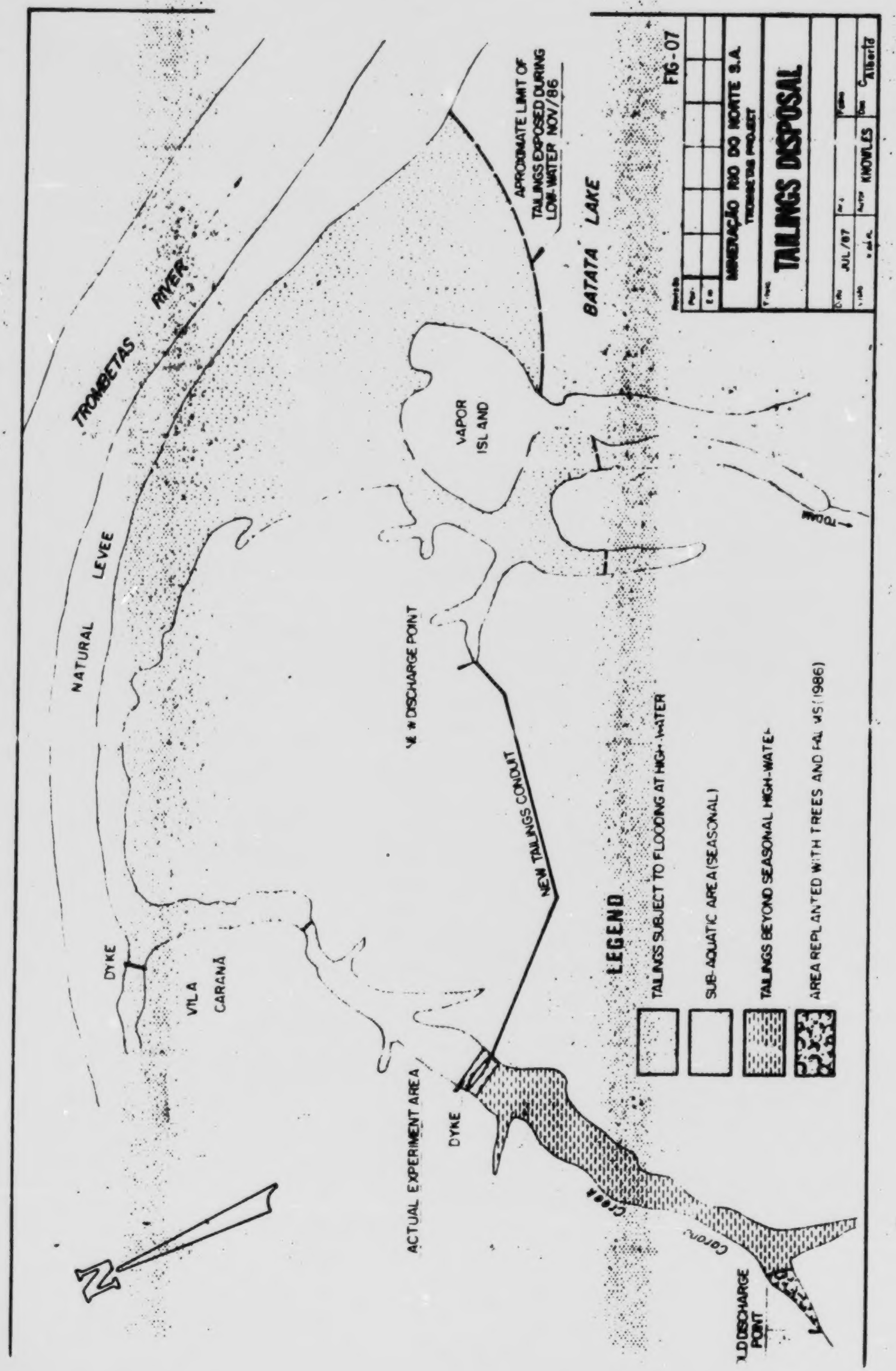
FIG-06

Revisão
Por
Em

MINERAÇÃO RIO DO NORTE S.A.
TROMBETAS PROJECT

Título
GRAIN SIZE DISTRIBUTION

Data JUL/87
Arq
Folha
Visto Lapa
Autor LAPA
Des C. Alberto


TROMBETAS RIVER
NATURAL LEVEE
VAPOR ISLAND
BATATA LAKE
APROXIMATE LIMIT OF TAILINGS EXPOSED DURING LOW-WATER NOV/86
½ # DISCHARGE POINT
NEW TAILINGS CONDUIT
DYKE
VILA CARANÁ
ACTUAL EXPERIMENT AREA
DYKE
Caranã Creek
OLD DISCHARGE POINT
LEGEND
TAILINGS SUBJECT TO FLOODING AT HIGH-WATER
SUB-AQUATIC AREA (SEASONAL)
TAILINGS BEYOND SEASONAL HIGH-WATER
AREA REPLANTED WITH TREES AND PALMS (1986)
FIG-07
MINERAÇÃO RIO DO NORTE S.A.
TROMBETAS PROJECT
TAILINGS DISPOSAL
JUL/87
KNOWLES
C. Alberto

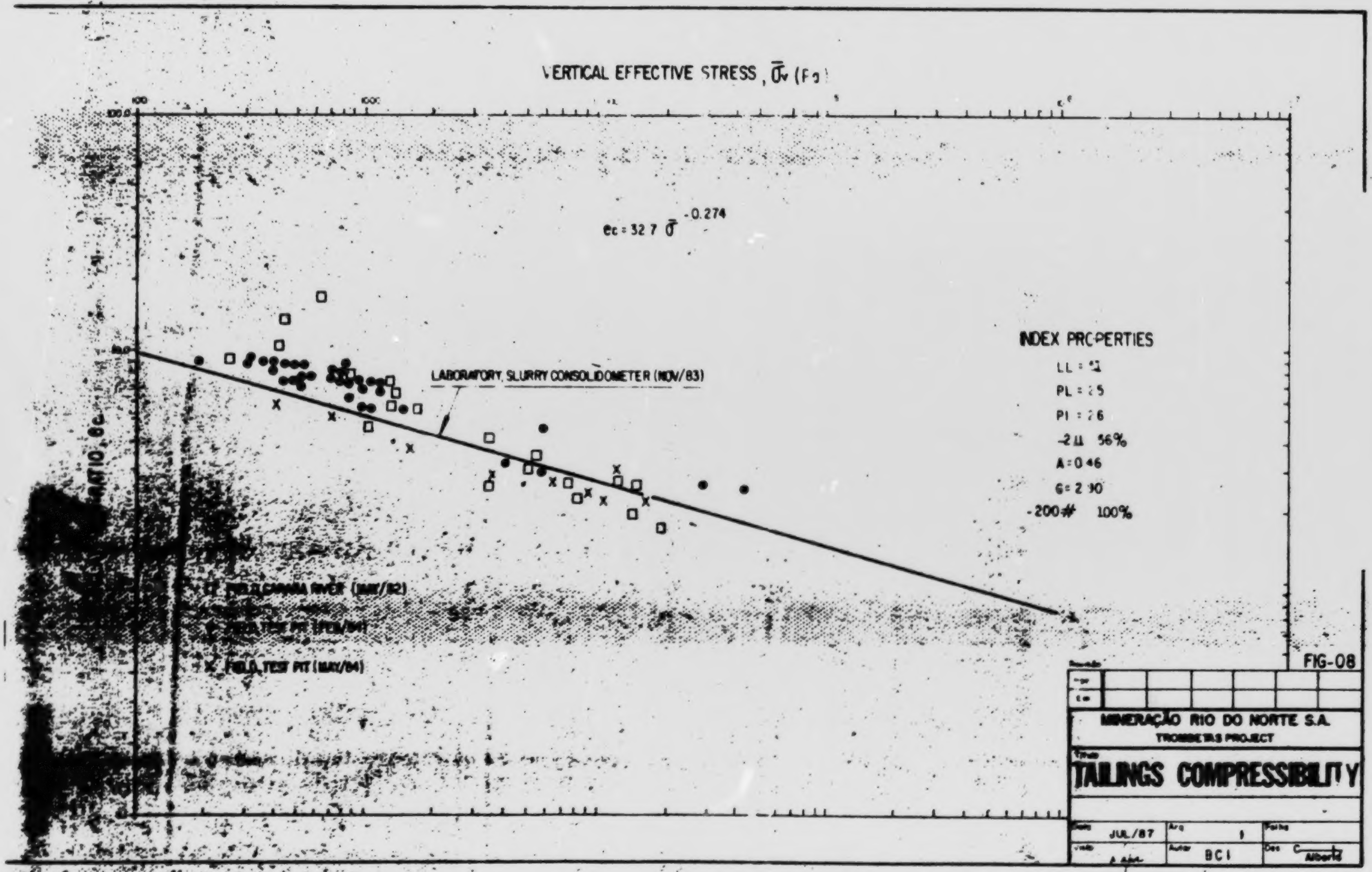

VERTICAL EFFECTIVE STRESS, $\bar{\sigma}_v$ (Pa)
100
1000
100.0
10.0
RATIO, ec
ec = 32.7 $\bar{\sigma}^{-0.274}$
LABORATORY SLURRY CONSOLIDOMETER (NOV/83)
INDEX PROPERTIES
LL = 51
PL = 25
PI = 26
-2μ 56%
A = 0.46
G = 2.90
-200# 100%
□ FIELD CANAMA RIVER (MAY/82)
● FIELD TEST PIT (FEB/84)
X FIELD TEST PIT (MAY/84)
MINERAÇÃO RIO DO NORTE S.A.
TROMBETAS PROJECT
TAILINGS COMPRESSIBILITY
JUL/87
1
BCI
Alberto

FIG-08

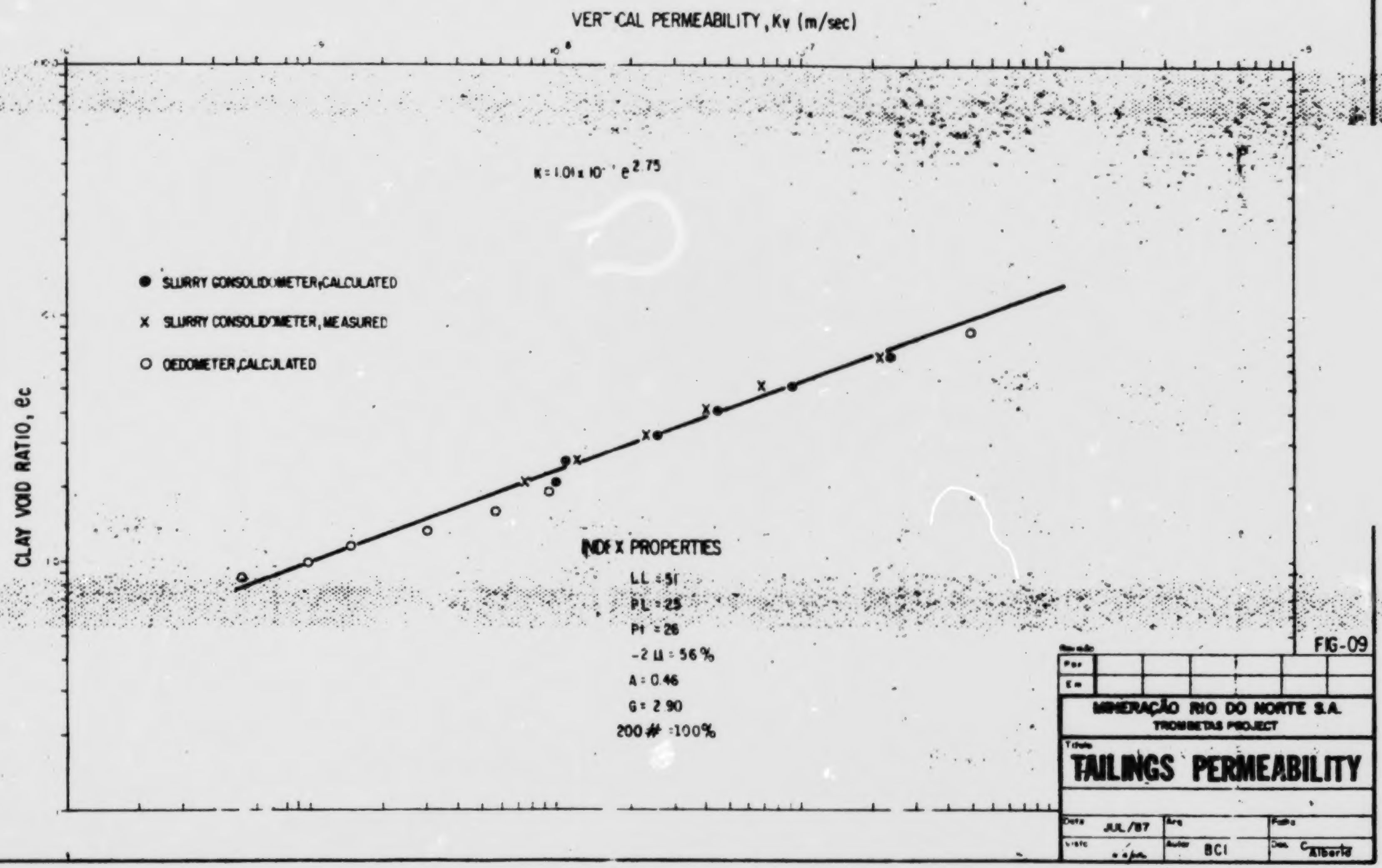
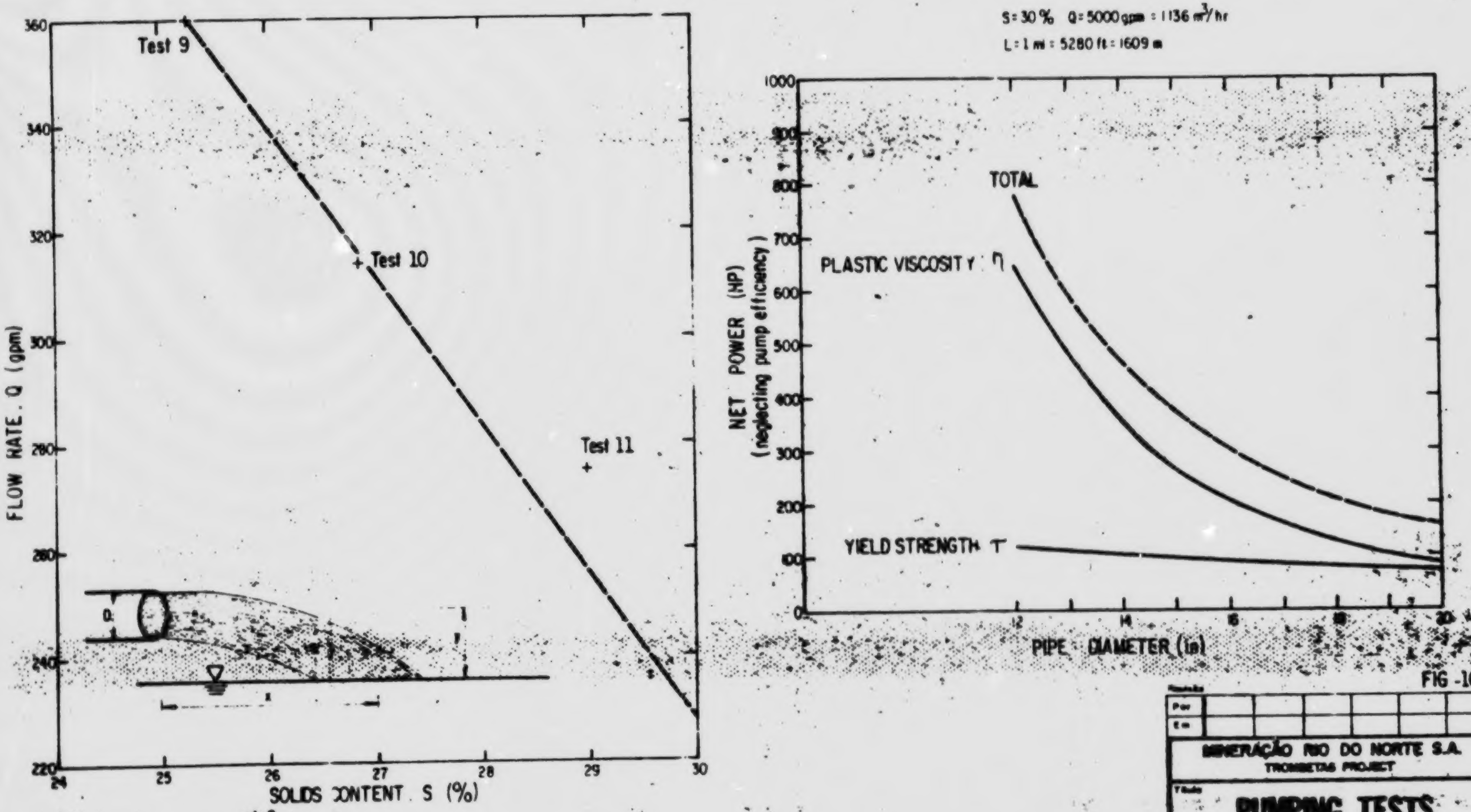


FIG-09

MINERAÇÃO RIO DO NORTE S.A.
TROMBETAS PROJECT

Título
TAILINGS PERMEABILITY



$D = 3\ 13/16"$ inches
$= 0.318$ feet

$A = \frac{\pi D^2}{4}$
$= 0.0793\ \text{feet}^2$

$V = \frac{x}{\sqrt{2y/g}}$

$Q = VA$

FIG -10

Por
Em

MINERAÇÃO RIO DO NORTE S.A.
TROMBETAS PROJECT

PUMPING TESTS

Data JUL/87
Visto
Autor BC1
Des. C Alberto

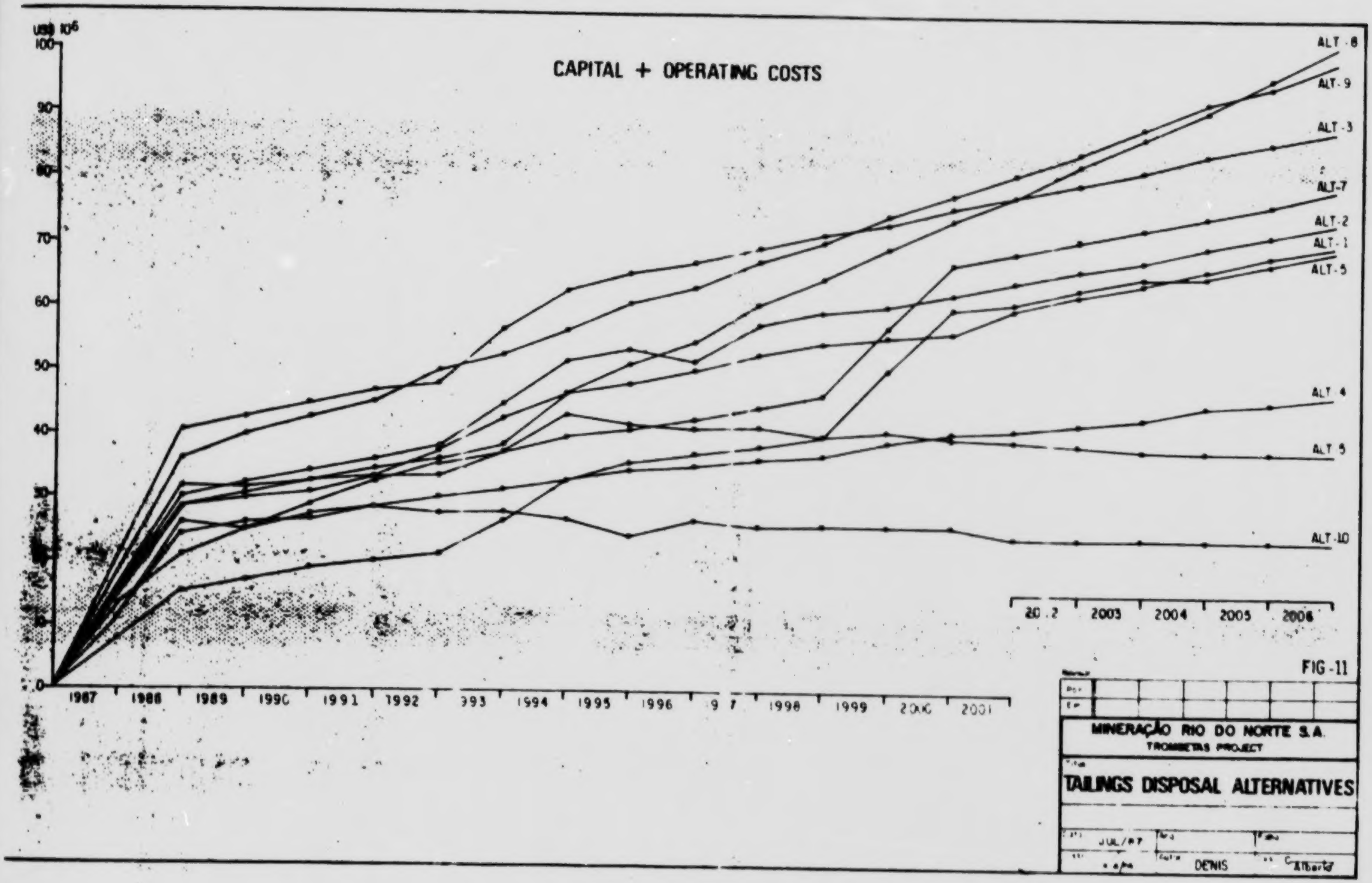

CAPITAL + OPERATING COSTS
US$ 10^6
100
90
80
70
60
50
40
30
20
10
0
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
ALT-8
ALT-9
ALT-3
ALT-7
ALT-2
ALT-1
ALT-5
ALT-4
ALT-5
ALT-10
MINERAÇÃO RIO DO NORTE S.A.
TROMBETAS PROJECT
TAILINGS DISPOSAL ALTERNATIVES
JUL/87
DENIS
C. Alberto

FIG-11

disposing of the tailings in the mined out areas.

The disposal of the tailings in the mined out areas also represents the best ecological alternative. The tailings are returned to their original source and revegetation will obliterate any signs of mining.

Tailings Disposal Project

The solution chosen diminishes to a great degree the environmental impact caused by the tailings.

The tailings coming from the washing plant at a solids content of 7 to 9%, will be pumped to an artificial pond. Over a certain period of time, settling of the tailings in this pond will result in a high solids content. A specially designed dredge, in which the pump is installed submerged next to the suction head, will enable the tailings to be pumped at a solids content of 25 to 30% to cells built in the mined out areas. The cells are just simple ponds formed by dykes built with the overburden material. In these cells the tailings will continue to settle to a higher density (Figure 12). The tailings will fill the cells in two stages, separated by an interval in order to permit good consolidation (Figure 13).

Roughly two years after the second filling of the cells the rehabilitation activities will start and the solids content expected at this time is around 59% (Figure 13).

The rehabilitation will be similar to the present day practice. The tailings and the tops of the dykes will be graded by bulldozer. Thereafter, the topsoil will be spread over the area to a thickness of 0.50 m to allow fast vegetation growth (Figure 14) and the ground will reflect a topography similar to that now obtained.

The dykes will be built by the existing draglines as part of the normal stripping operation. As a consequence, no significant increase in operating costs due to the cell construction is foreseen.

The implementation of this project started in September 1986. The new tailings disposal system will become operational during the second half of 1989.

Simultaneously, efforts are being dedicated to reclaim the silted areas of Batata Lake. Studies have already started to find out the best way to reclaim these areas when the discharge of the tailings into the lake is phased out.

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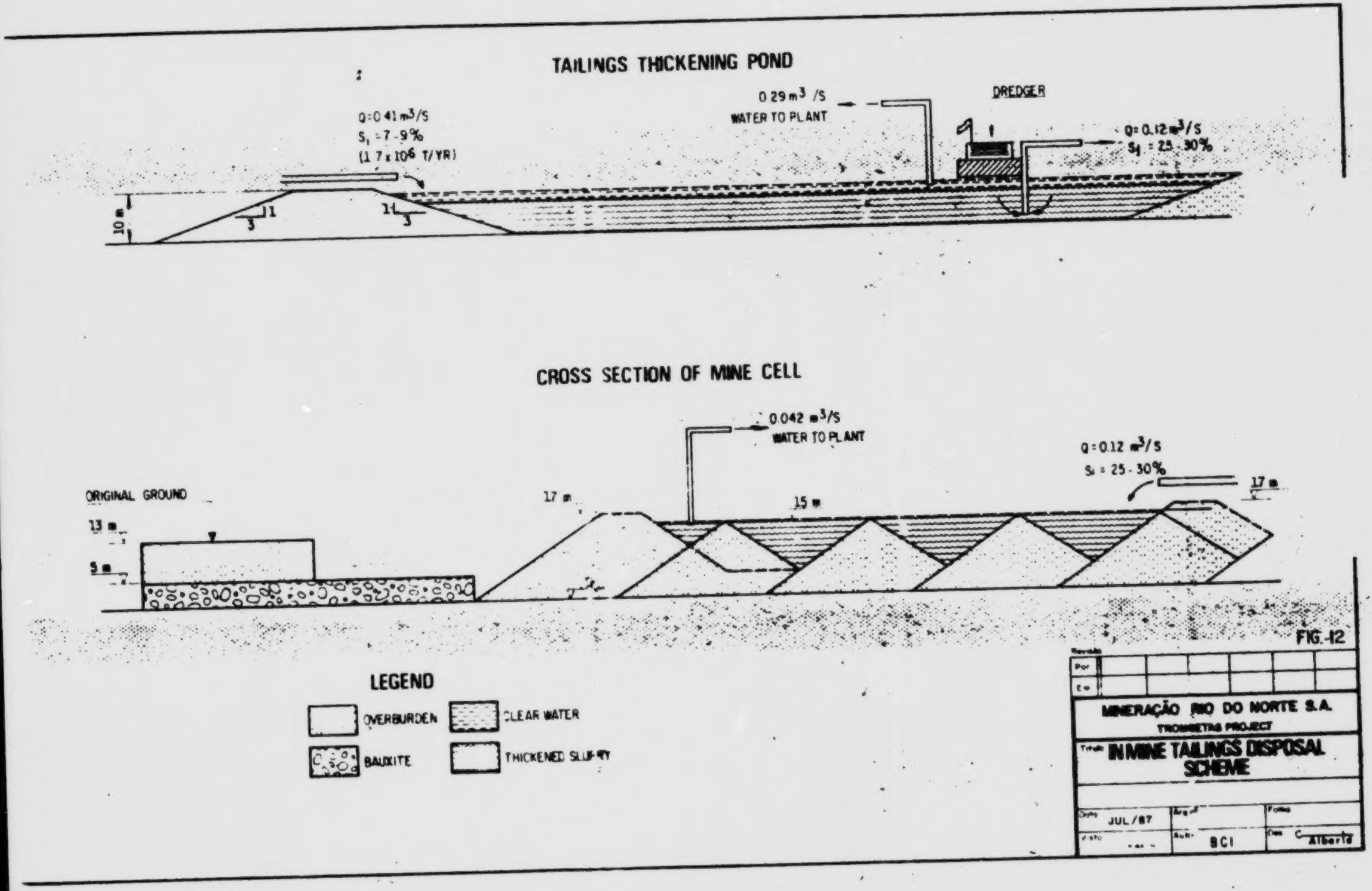
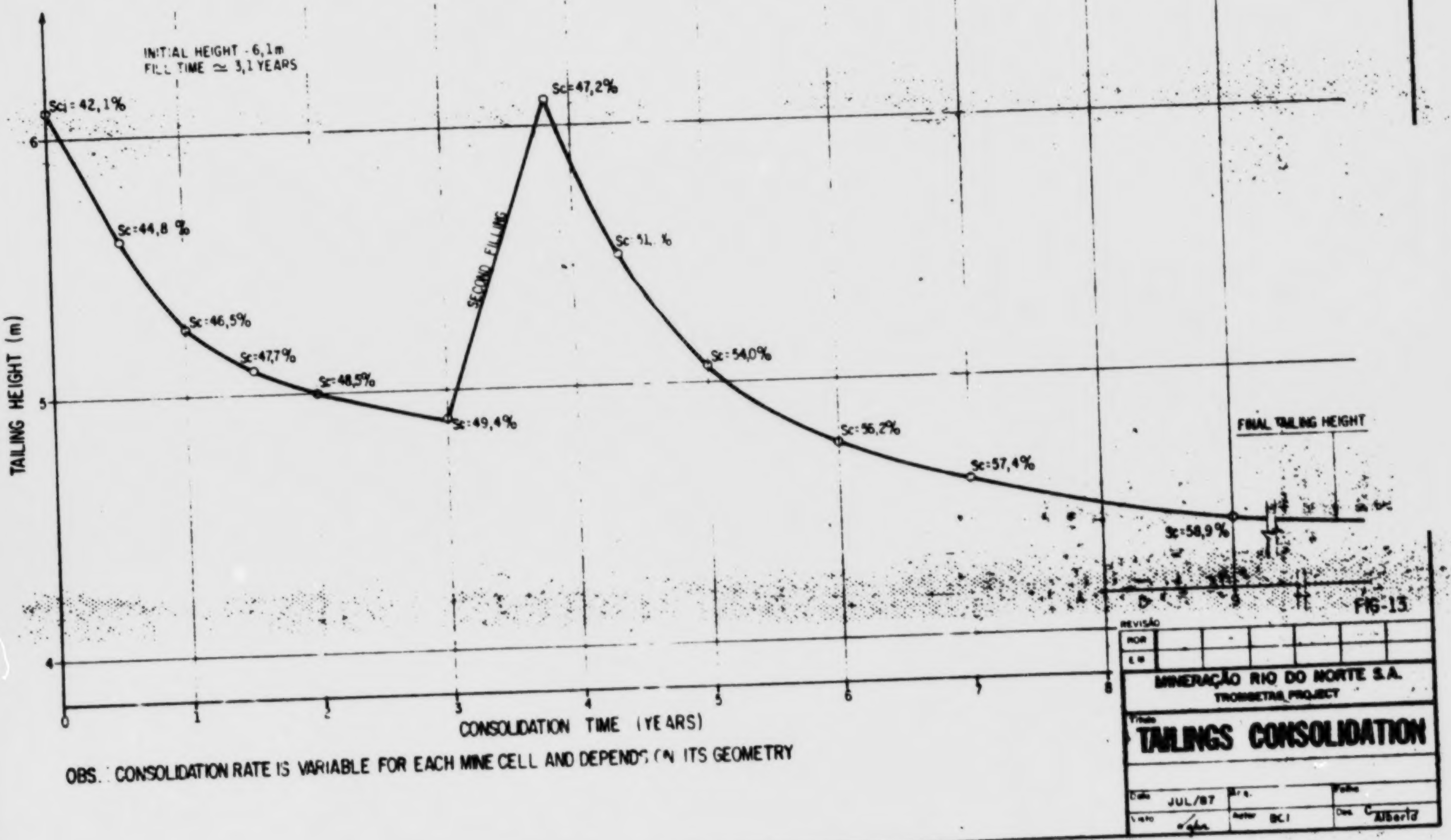

TAILINGS THICKENING POND
Q=0.41 m³/S
S₁ =7-9%
(1.7 x 10⁶ T/YR)
1
3
1
3
10 m
0.29 m³ /S
WATER TO PLANT
DREDGER
Q=0.12 m³/S
S₁ = 25-30%
CROSS SECTION OF MINE CELL
0.042 m³/S
WATER TO PLANT
Q=0.12 m³/S
S₁ = 25-30%
ORIGINAL GROUND
13 m
5 m
17 m
15 m
17 m
LEGEND
OVERBURDEN
CLEAR WATER
BAUXITE
THICKENED SLURRY
Revisão
Por
Em
MINERAÇÃO RIO DO NORTE S.A.
TROMBETAS PROJECT
Título IN MINE TAILINGS DISPOSAL SCHEME
Data JUL/87
Visto
Arq.
Aut. BCI
Folha
Des. C. Alberto

FIG. 12



OBS.: CONSOLIDATION RATE IS VARIABLE FOR EACH MINE CELL AND DEPENDS ON ITS GEOMETRY

FIG-13

MINERAÇÃO RIO DO NORTE S.A.
TROMBETAS PROJECT

TAILINGS CONSOLIDATION

JUL/87
BCI
C. Alberto

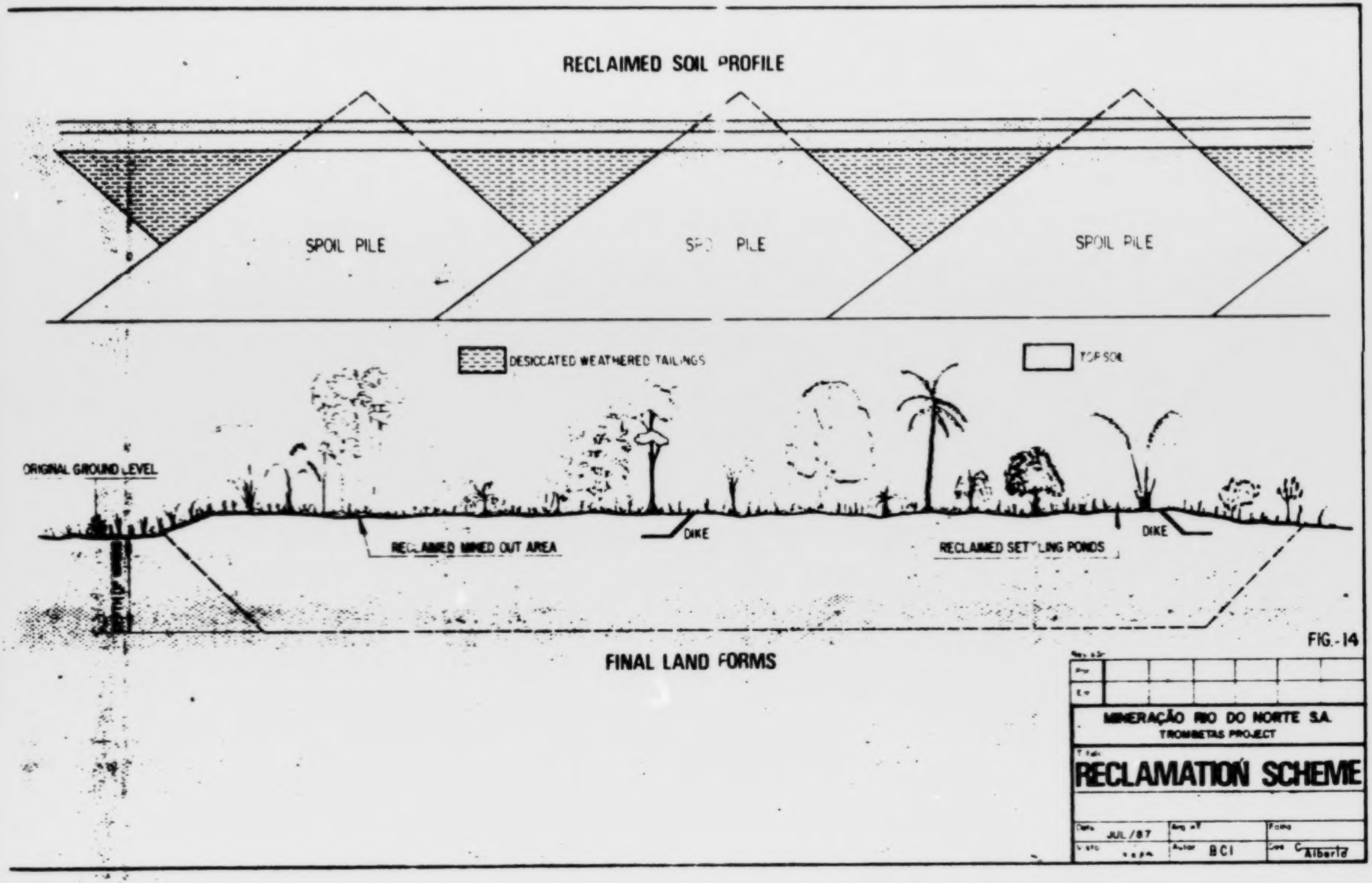

RECLAIMED SOIL PROFILE
SPOIL PILE
SP PILE
SPOIL PILE
DESICCATED WEATHERED TAILINGS
TOP SOIL
ORIGINAL GROUND LEVEL
RECLAIMED MINED OUT AREA
DIKE
RECLAIMED SETTLING PONDS
DIKE
FINAL LAND FORMS
MINERAÇÃO RIO DO NORTE S.A.
TROMBETAS PROJECT
RECLAMATION SCHEME
JUL /87
BCI
C. Alberto

FIG.-14

Greig, E.W. 1977. Trombetas and other Amazon bauxites, Brazil, AIME preprints - 77/H/92. pp 34.

Lapa, R.P. and C.M. Hernalsteens. 1985. The Trombetas bauxite, Mining in Brazil, DNPM.

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RECENT TRENDS IN PHOSPHATE MINE RECLAMATION IN THE UNITED STATES[1]

by

Wayne R. Marion[2]

Abstract. Phosphate mining has occurred in several regions of the United States, including portions of Florida, North Carolina, Tennessee, Idaho, Montana, Utah, Wyoming, and California. About 85 percent of the combined total U.S. phosphate production comes from Florida and North Carolina, while the western states account for 10 percent, and Tennessee produces 5 percent. Phosphate rock is mined under different physical and ecological conditions in each of these states and this leads to differences in reclamation requirements and expectations. Also, the political climate associated with phosphate mining is highly variable from state to state and this has been reflected in reclamation regulations. Florida has the most rigorous environmental standards and reclamation regulations of any of the states mentioned, with North Carolina, western states, and Tennessee, respectively, having less rigorous restrictions and fewer reclamation regulations. Reclamation regulations and changes in resulting reclamation were documented on a state-by-state basis over the 5-year period, 1983-88. In Florida, revisions of the reclamation regulations over this interval have resulted in changes in emphasis from an early focus on re-establishing wetlands to a more recent emphasis on redeveloping drainage patterns and upon reclaiming to upland forests. Reclamation changes in other states have been more subtle, with subsequent land use and economic considerations often dictating requirements for reclamation.

Additional Key Words: Phosphate mining, reclamation, regulations, trends

Introduction

Phosphate mining in the United States is typically accomplished using surface strip mining techniques and, in some states, this has resulted in major alterations of drainage patterns, landscape features and vegetative communities. Phosphate reclamation regulations have evolved in nearly every state with this mining activity and the implementation of these regulations often being controversial as various regulatory agencies, phosphate industry, environmental groups, and other concerned groups have sought to provide input into the process. As these various groups have tried to clarify, further regulate, or negotiate various provisions of reclamation regulations, confusion over interpretation and enforcement of specific reclamation provisions sometimes has resulted in both backlogs and delayed implementation schedules for mandatory reclamation. For example, in Florida where about 76 percent of the nation's phosphate is mined (Stowasser 1986), reclamation has been required since 1975 on all lands altered by phosphate mining. However, of the 32,500 hectares of land in Florida disturbed by this mining since 1975, only 40 percent has been reclaimed (Florida Department of Natural Resources 1989).

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[1] Paper presented at the Conference "Reclamation, A Global Perspective", Calgary, Alberta, Canada, August 27-31, 1989. This paper is contribution 10037 of the Florida Agricultural Experiment Station, Gainesville.

[2] Wayne R. Marion is an Associate Professor and Extension Wildlife Specialist, Department of Wildlife and Range Sciences, University of Florida, Gainesville, FL. 32611.

Phosphate reclamation regulations are presumed to represent the currently negotiated state-of-the-art for each state, despite the fact that they are concurrently being modified and evolving in some states. By examining the similarities and differences between states and regions involved in phosphate mining, it is possible to develop some generalizations regarding the relative sophistication of reclamation procedures and environmental concerns. This paper is an attempt to compare and contrast phosphate mining regulations and reclamation nationwide and to explore recent trends associated with these topics. Emphasis will be placed upon the ability of reclamation programs to replace natural contours and drainage patterns, vegetation, and ecosystem function.

Methods

Interviews with phosphate mine operators and regulatory agency officials were personally conducted in the fall of 1983 at nearly all locations of mine reclamation activity in the United States. Also, during this process, representative mines were visited and reclamation sites were photographed in two districts of Florida and in appropriate regions of Idaho, North Carolina, and Tennessee. Slightly more than 5 years later (early in 1989), copies of the most recent phosphate reclamation regulations were obtained from the appropriate agencies in each of these states and were qualitatively compared with the 1983 reclamation regulations. Any major changes were noted in these reclamation regulations over the 5-year interval particularly as they affect reclamation back to natural ecosystems in each state.

Results

Reclamation of lands disturbed by phosphate mining has been required since the early to mid-1970's in most states discussed in this paper. Land reclamation involves a variety of technologies and regulations that illustrate the complexity of economical, ecological and political forces involved in the decision-making process. The magnitude of disturbance and size of mining operations in each of the states are strong determinants of the types of reclamation that are appropriate and the degree of associated environmental concern. Florida dominates phosphate mining activities in the U. S. with a total of over 70,000 hectares disturbed since mining began in the state. In Maury County, Tennessee, approximately 5,000 hectares have been mined for phosphate; this land area is over twice as large as the 2,000 ha of land mined for phosphate in Idaho and western Wyoming. In coastal North Carolina, one mining company has disturbed about 1500 ha of land so far, but the phosphate reserves in the Pungo River formation of this state are thought to exceed 140,000 additional hectares (Schaller and Sutton 1978). Phosphate mining in California has been restricted to about 100 hectares disturbed several years ago but this area has not yet been reclaimed (H. Record 1983 pers. comm.).

Florida.

The dominance of Florida in the magnitude of disturbance and production of phosphate in the United States will be reflected in this paper due to the readily available sources of information and research on this topic. The magnitude of phosphate mining in Florida and the high level of public concern has resulted in substantial involvement by agencies and organizations in the permitting and review process, including at least four at the federal level, nine at the state level and numerous local organizations (Marion 1986). Florida has by far the most sophisticated phosphate reclamation technology, environmental concerns and reclamation options of any state in the country. State agencies, particularly the Department of Natural Resources and the Department of Environmental Regulation, are the primary governmental entities reviewing reclamation applications, implementation, and completion in Florida.

Early reclamation regulations relating to natural ecosystems dealt with water quality standards, slopes and sizes of wetlands and other water bodies, and minimal requirements and timing for re-establishing ground cover on reclaimed sites. The traditional reclamation in Florida has been mostly to pastures, with some citrus groves or other agricultural croplands and many "land and lakes" wetlands where rounded peninsulas are interspersed and form the meandering shorelines of reclaimed lakes. More recent revisions of the reclamation regulations in Florida involve more detailed physical and biological descriptions of the property. This includes consideration of original drainage patterns and detailed design of wetlands to include both deep and shallow areas, protection of endangered flora and fauna, planting of at least 10 percent of upland sites in native trees and shrubs, and provision of a greenbelt of indigenous trees and shrubs around wetlands. In most cases, these revisions of the reclamation regulations in Florida represent improvements in the reclamation process to provide for natural ecosystem functions. A publication by King et al. (1985) was instrumental in providing on-site reclamation guidelines to the industry that provided numerous illustrations of innovative ways to reclaim and connect wetland and upland sites. As reported in another paper (Marion and King 1988), the early reclamation in Florida emphasized restoration of wetlands, but more recent emphasis has been on providing more indigenous upland forests. The importance of upland forests has appeared in provisions of the reclamation regulations and on the landscape as this reclamation is implemented.

North Carolina.

Phosphate mine reclamation has been required in North Carolina since the enactment of the Mining Law of 1971, a law that required acre-for-acre reclamation within two years after the completion of active mining. This law has been amended at least twice since then (1981 and 1987) to include minor additions and changes in bonding (D. Stewart 1989 pers. comm.). Mining operations and reclamation in North Carolina are overseen by a Mining Commission that serves as a first line of decision-making to resolve any differences between the phosphate industry and regulatory agencies. The phosphate mine reclamation regulations appear to be broad and relatively flexible in this state -- they do not require reclamation back to pre-mining conditions, but generally do require that the land is put back in a "useful" condition. A major purpose of the Mining Act of 1971 was "to provide that the usefulness, productivity, and scenic values of all lands and waters involved in mining within the State will receive the greatest practical degree of protection and restoration." In many respects, the most stringent environmental regulations affecting phosphate mining in North Carolina are promulgated by federal agencies such as the U. S. Army Corps of Engineers and the U. S. Fish and Wildlife Service. The former agency's standards protecting coastal wetlands are probably the most stringent of any of the regulations affecting mining in this state. In 1988, a major violation of air and water quality standards resulted in a $ 5 million fine against the company mining phosphate in North Carolina; this violation and increasing public pressure is causing this company to respond more positively to environmental regulations.

In many ways, phosphate mining operations in North Carolina appear to be similar to operations in Florida. Mining in both of these states is accomplished by open pit strip mining as the underlying matrix containing phosphatic clay is brought to the surface from various depths (10-15 m in Florida, 25-30 m in North Carolina). Because phosphatic clays are extracted from nearly twice the depth in North Carolina as in Florida, initial phases of strip mining in North Carolina normally involve flooding the area and using hydraulic dredges to remove the upper third of the soil prior to draining and excavation of the mine with electric draglines. At least three major "waste" by-products result from phosphate mining operations in both states; these include (1) overburden soils, (2) sand tailings, and (3) phosphatic clay "slimes". The reclamation and revegetation of these materials was discussed in some detail by Farmer and Blue (1978).

In both North Carolina and Florida, a high proportion (60-70 percent) of the landscape in and near the mine becomes phosphatic clay settling ponds. These settling ponds result when an area of unreclaimed overburden spoil piles and mine cuts is surrounded by a dike and inundated with "waste" clay slurry left after the removal of phosphate particles from the saturated clay matrix. This procedure of disposal of "waste clays" in these diked impoundments typically delays reclamation of these mined areas for long periods of time (e.g. 10-15 years). In North Carolina, well over half of the total area mined has been inundated with settling ponds since mining resulting in there being little reclamation to adequately evaluate (D. Stewart 1989 pers. comm.). Thus, in North Carolina and Florida, the need for disposal sites for large volumes of waste clays in suspension has both created vast areas of new wetlands on the landscape and delayed initiation of reclamation for several years. Phosphate settling ponds are extremely attractive habitats for a number of wildlife species groups, especially waterfowl and wading birds. The values associated with these ponds as habitats for birds have been previously assessed and are thought to be both beneficial and detrimental for wildlife species (Marion 1989).

In general, environmental regulations associated with phosphate mining in North Carolina have not developed either to the extent or sophistication of those in Florida. Recent evidence suggests that public pressure on the industry in North Carolina is beginning to cause some changes and regulations will likely further evolve, but this is occurring slowly.

Tennessee.

Tennessee has been requiring reclamation of phosphate lands since enactment of the Mineral Surface Mining Law of 1972 and the amendments in 1980. A relatively modest performance bond is necessary to be filed with the state of Tennessee in order to legally mine for phosphate. Unlike several other areas where phosphate mining exists (e.g. Florida, Idaho, and North Carolina) and where the ultimate land use after reclamation is only vaguely known, the intended land use after mining for phosphate in Tennessee is clearly known and is usually agricultural pasturelands or grain fields. The mining in this state is generally small-scale, shallow (3-4 m) strip mining using relatively small equipment and causing, at most, only a temporary disruption of the surface. Prior to mining, the landowner generally specifies the vegetation to be used in post-mining reclamation that typically is pasture grass (e.g. fescue, sweetclover, Sudangrass, orchardgrass) or agricultural crops (e.g. corn, oats, soybeans, barley, and alfalfa).

Phosphate mining in this state is extremely localized and normally goes from a pasture back to a pasture within a matter of weeks or months, depending mostly on the time of year and weather conditions. Because agriculture is the existing and likely future land use in the area, landowners have minimal incentives to plant either pine trees (which grow poorly in south-central Tennessee) or hardwoods (slow growth and often poor investment) on their lands following mining. Development of or enhancing wildlife habitat values on the landscape following mining are essentially being overlooked on upland sites. A major landform resulting from the phosphate mining operation is the establishment of large, deep slurry ponds; these are being retained as open water areas with abundant fish populations and some use by waterfowl. As in Florida, long-term maintenance of these ponds as wetlands or lakes will depend upon having an adequate supply of water (currently coming from mining operations). Some mining operations have closed recently in Tennessee, leaving the future uses and potential recreational benefits of these areas in jeopardy.

Western States.

Phosphate mining in the western states is considerably different from mining in the southeastern states and it is therefore difficult to make valid, direct comparisons. Although most mining is being conducted in southeastern Idaho, phosphate mining also has occurred in portions of California, Montana, Utah and Wyoming. In Idaho, phosphate mining began in 1909 at the Waterloo Mine and is expected to continue in the area for several more decades. About 35 percent of the phosphate reserves in the United States are in southeastern Idaho and much of this is close enough to the surface to be strip mined (Evans 1984). Phosphate is mined from sedimentary rock layers that have been severely faulted and uplifted by crustal movements. Phosphate mining is accomplished by strip-mining of selected layers containing ore in mountainous terrain; large, rocky, relatively unstable waste dumps are the focus of reclamation efforts.

Since many of the lands mined for phosphate are owned by the U.S. Forest Service, this agency has taken the lead in establishing stability and revegetation stipulations. The stated policy of the Caribou National Forest (20,000 acres currently leased for phosphate mining) regarding mined land reclamation is: "The short term reclamation objective is the immediate reduction and prevention of erosion, by stabilizing the soil with adaptable plant species. The long term goal is to return the land to an end use similar to that which existed prior to mining at a level of productivity equal to or better than that previously realized. The reclamation plan which accompanies each mining plan will incorporate a long term revegetation plan." Attempts at reclamation in Idaho began in 1958 and has evolved since then; recently, detailed reclamation guidelines were outlined in an R-4 Reclamation Field Guide (Albrechtsen and

Farmer undated). The "waste" materials that remain after phosphate mining in the Idaho foothills are limestones, cherts, medium waste shales, mined out areas and catchment basins. Limestones and cherts are usually large, rocky materials that are buried during the reclamation process.

Reclamation technology includes procedures to meet, but not to exceed, the U.S. Forest Service's stipulations on slopes (3:1 or flatter) and on revegetation (67 percent cover over 90 percent of the area within 3 years after completion of mining). Heavy equipment has typically been used to recontour waste shale dumps wherever they existed following mining and these sites are typically harrowed, fertilized and seeded with a rangeland drill or by broadcast seeding. To reduce erosion and to meet the revegetation requirements, the normal strategy has been to plant grasses and forbs (Richardson and Farmer 1983) while experimenting with re-establishment of shrubs and trees (which takes several years). Strong, local pressures exist to open up recently reclaimed and revegetated lands to grazing (Francis 1984) and to maintaining these lands as grazeable pastures, rather than allowing them to naturally return to forested lands. Control and supervision are necessary to restrict early and over-grazing of recently revegetated sites. Although phosphate mining was controversial from an environmental perspective in the mid-1970's, these operations appear to be less so now and the reclamation stipulations in Idaho have been relatively well-established for several years.

Conclusions

Phosphate reclamation regulations appear to be relatively stable in Idaho, just as they were in North Carolina and Tennessee. In Florida, where reclamation regulations have shown the most growth and sophistication, these regulations continue to evolve and be revised to "fine-tune" reclamation on the landscape. In general, this study confirmed several trends --primarily that the magnitude of mining disturbance in each state or region directly affects the sophistication of environmental concerns, reclamation regulations, and revegetation combinations. The extent of local disturbance was found to be minimal in Tennessee, intermediate in Idaho and North Carolina, and extensive in Florida. The reclamation technology employed in most states has been selected based upon extent of disturbance, previous company experience, and economic considerations.

Revegetation of phosphate mines has generally involved establishing a grass cover within time limitations and budgetary considerations. Most states have developed experimentation/demonstration of other revegetation options (e.g. various shrubs and trees), but the incentives to explore and/or widely implement these options over broad areas have been lacking. Generally, phosphate lands are reclaimed for eventual use as pastures or other agricultural lands. Reclamation in Florida involves considerably more experimentation and demonstration (e.g. crop, shrub and tree planting) than most other states involved in phosphate mining. Reclamation of at least a portion (25-30 percent) of disturbed landscapes back to natural ecosystems that have natural functions and intrinsic values for fish and wildlife resources (as described by Marion and King 1988) remains a worthy goal and challenge.

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MINING AND RECLAMATION OF PRIME FARMLANDS IN WESTERN NORTH DAKOTA[1]

by
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ABSTRACT. Prime farmland reclamation is required by the 1977 Surface Mining Control and Reclamation Act. The Coteau Properties Company operates a lignite mine in western North Dakota, and is the only mine in the semiarid west to mine and reclaim large acreages of prime farmland. The characteristics of prime farmlands in western North Dakota are not addressed by Federal regulatory requirements, and conflict with State requirements for reclamation of all croplands in North Dakota. This conflict results in unnecessary additional environmental disturbance during mining, and increased reclamation expense to the mine operator. Reclamation operations at the Freedom Mine are described. Recommended changes to prime farmland regulations and interpretations of existing regulations would enhance overall reclamation for all croplands in western North Dakota, both prime and nonprime.

Introduction

The Coteau Properties Company operates the Freedom Mine, a large surface coal mine in western North Dakota. Most land mined and reclaimed has an agricultural land use, and some is classified by the U.S.D.A. Soil Conservation Service as prime farmland. The Freedom Mine is the only surface mine west of the 100th meridian to reclaim significant acreages of prime farmland. This paper discusses mining and reclamation of prime farmlands at the Freedom Mine, and provides recommendations to enhance reclamation by reducing environmental disturbance and costs.

The Soil Conservation Service (SCS) has recognized prime farmland as "land best suited for producing food, feed, forage, fiber, and oilseed crops and also available for these uses although it may be currently used for cropland pastureland, or rangeland" (SCS 1977). The SCS, and other policy-making and regulatory agencies, place a high value on prime farmlands, and recognizes the importance of conserving these valuable agricultural lands for future generations. Describing and mapping prime farmlands helps government agencies establish policies and regulations to stem the loss of the nation's most productive croplands (SCS 1977). Specific criteria are used by the SCS to determine if a soil should be considered prime. (Federal Register 1978)

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Currently about 65 soils in North Dakota are classified as prime; an additional 100 would qualify as prime if drainage or irrigation practices were applied (Doll 1986). The North Dakota Public Service Commission has additional rules to determine if special prime farmland soil handling and reclamation requirements apply. For example, with regard to surface mining, prime farmland regulations are not applicable to those lands not historically cropped (State of North Dakota 1987).

Site Description

The Freedom Mine is located about 90 miles northwest of Bismarck, North Dakota. Over 11 million tons of lignite coal are mined annually. About half the coal mined is delivered to the adjacent Antelope Valley Station, an 880mw electrical generating station. The remainder is delivered to the Great Plains Coal Gasification Project, also adjacent, where it is converted to synthetic natural gas. Mining began in 1983, following several years of preliminary development.

The mine permit covers approximately 6,000 acres, and active operations occupy about half the permit area. Average annual disturbance is 3-400 acres. Final reclamation of mined lands began in 1986. Over 700 acres have been reclaimed to date. Of the more than 500 acres of cropland reclaimed, some 140 acres have been reclaimed as prime farmland. All cropland, including prime farmland, is seeded with a "pre-crop" hayland mixture of smooth bromegrass, intermediate or pubescent wheatgrass, and alfalfa. Reclaimed croplands and prime farmlands are mixed together in a mosaic throughout the landscape, similar to the premine condition, and are managed identically. Production data are collected separately for prime and nonprime areas, as required by law.

Cropland areas are dominated by soils of glacial origin. Major soils are classified as Argiborolls or Haploborolls (SCS 1978). Zahl, Williams, and Bowbells soils comprise most of the permitted cropland. They are very similar; the primary difference between these soils is the thickness of

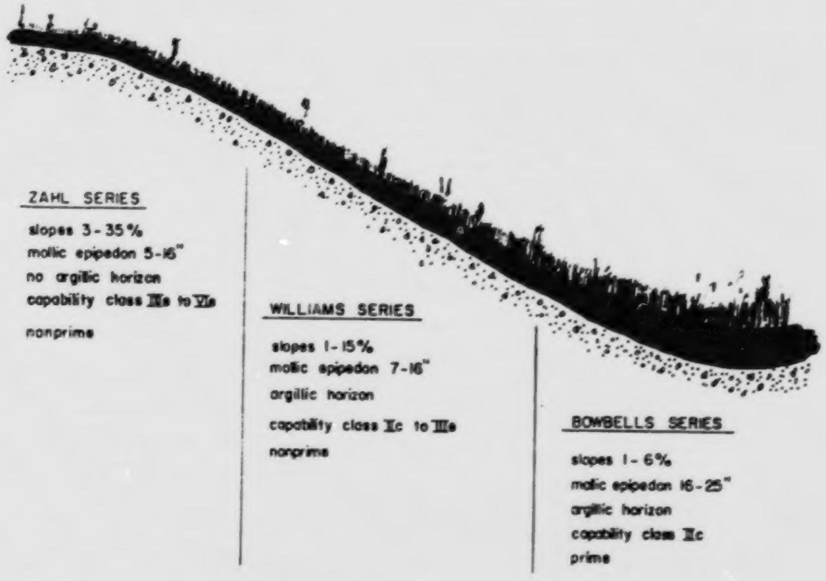

ZAHL SERIES
slopes 3-35%
mollic epipedon 5-16"
no argillic horizon
capability class IIIe to VIe
nonprime
WILLIAMS SERIES
slopes 1-15%
mollic epipedon 7-16"
argillic horizon
capability class IIc to IIIe
nonprime
BOWBELLS SERIES
slopes 1-6%
mollic epipedon 16-25"
argillic horizon
capability class IIc
prime

Figure 1. Cross-section comparison of three dominant soils at the Freedom Mine. Parent material for all three soils is calcareous loamy glacial till. Information from SCS 1978.

the mollic epipedon, and lack of an argillic horizon in Zahl soils. These three dominant soils occur adjacent to each other in the landscape, and can most easily be differentiated by their landscape position (Figure 1).

Prime farmlands in western North Dakota are largely the result of favorable landscape position. Several authors have noted enhanced crop production on lower slopes, drainages, valleys, and swales, due to runon water from above (Veneman and Bodine 1982, Land Reclamation Research Center 1988, Richardson and Wollenhaupt 1983, Wollenhaupt and Richardson 1982, Richardson 1983, Schroeder and Doll 1984).

Once stripped by tractor-scrapers, the distinguishing characteristics of soil thickness and landscape position are eliminated. In many parts of the United States there is a significant difference, in physical and chemical characteristics, between adjacent prime and nonprime soils. In western North Dakota, however, prime and nonprime soil materials, once removed from the landscape, are very similar. A review of important characteristics shows little or no difference between prime and nonprime material (Stomberg 1985, SCS 1978, Figure 2). Carter and Doll (1983) compared crop growth on western North Dakota prime and nonprime topsoil, under similar greenhouse conditions, and found no significant differences between them.

Prime Farmland Requirements

Because of the recognized importance of prime farmlands as a source of food and fiber, the Federal government developed special regulations for prime farmland reclamation following surface mining (P.L. 95-87 1977, Federal Register 1983). These rules are more stringent than those for other lands, including nonprime croplands. Highlights of these special rules are:

1) Prime farmlands must be reclaimed to 100% of their premine productivity; all other lands must be reclaimed to 90% of their premine productivity.

Freedom Mine Topsoil Samples (Averages)

	n	EC (mmho/cm)	SAR	CCE *	OM (%)	Depth (in.)
Prime	18	0.96	0.82	4.56	2.79	24
Non-Prime	46	0.72	0.37	4.48	3.02	18

* Calcium carbonate equivalent

Range of Topsoil Properties

Soil Type	Depth (in.)	Topsoil Texture (USDA)	Permeability (in./hr.)	Available Water (in./in.)	Salinity (mmho/cm)	pH
Bowbells (prime)	0-11	Loam	0.6-2.0	0.17-0.24	less than 2	6.1-7.3
Williams (non-prime)	0-7	Loam	0.6-2.0	0.17-0.24	less than 2	6.6-7.3
Zahl (non-prime)	0-5	Loam	0.6-2.0	0.17-0.22	less than 2	6.6-7.8

Figure 2. Comparison of prime and non-prime topsoil sampled at the Freedom Mine (Stomberg 1985), and the range of topsoil properties for dominant soils found at the Freedome Mine (SCS 1978).

2) For prime farmlands, both topsoil (A and part of the B horizon) and subsoil (B and C horizons) must be salvaged, and are to be stripped and respread separately; for other lands mined, only topsoil is required to be salvaged.

3) Prime farmland topsoil must be kept separate from nonprime topsoil; topsoil mixing is allowed, however, if nonprime topsoil is proven to have "greater productive capacity" than prime topsoil.

4) Prime farmland subsoil must be kept separate from nonprime subsoil; subsoil mixing is allowed, however, if nonprime subsoil is found to be "equally or more favorable for plant growth".

5) A minimum 48" of suitable plant growth material (topsoil and subsoil) is required to be respread for reclamation of prime farmlands; no specific respread depth is mandated in Federal regulations for reclamation of other lands.

6) Three years of crop production is required to determine successful reclamation of prime farmlands; for other lands, including nonprime croplands, reclamation success is based on two years of crop production.

7) The U.S.D.A. Soil Conservation Service has developed soil handling and soil profile reconstruction specifications for prime farmland only; regulatory agencies use these to evaluate surface mine operators' plans for mining and reclamation of prime farmlands.

North Dakota surface mining regulations, for reclamation of all lands, are much more stringent than those of other states, or even Federal regulations. For all mined lands, including both prime farmland and nonprime cropland, North Dakota's rules require:

1) All lands must be reclaimed to 100% of their premine productivity.

2) Topsoil (A and part of the B horizon) and subsoil (B and C horizons) must be salvaged, and must be stripped and respread separately.

3) All soil must be kept separate by landowner during mining and reclamation, to assure each landowner has his own soil returned to his land.

4) A detailed soil survey, mapped at a scale 1:4,800, is required to identify available soil quantity and quality, and is used to determine how much topsoil and subsoil is available to salvage.

North Dakota's reclamation regulations provide the same amount of protection for all lands that Federal regulations provide for prime farmlands only. In this respect, all land reclamation in North Dakota is performed in a manner consistent with the goals of Federal prime farmland regulations. The current overlap of Federal prime farmland regulations with State regulations causes conflicts, which result in lesser environmental protection and greater cost for cropland reclamation in North Dakota.

Beginning in 1975, up to five feet of topsoil and subsoil was required to be salvaged from all lands to be mined in North Dakota. This requirement addressed underlying clay overburden having high sodium adsorption ratios, detrimental to plant growth. However, much of the overburden in western North Dakota is high quality glacial till; some is equivalent to overlying subsoil, with regard to important physical and chemical characteristics, and is similarly suitable for plant growth. Years of research indicated a five foot soil respread was not always necessary to return 100% postmine productivity (Doll et al 1984, Barth and Martin

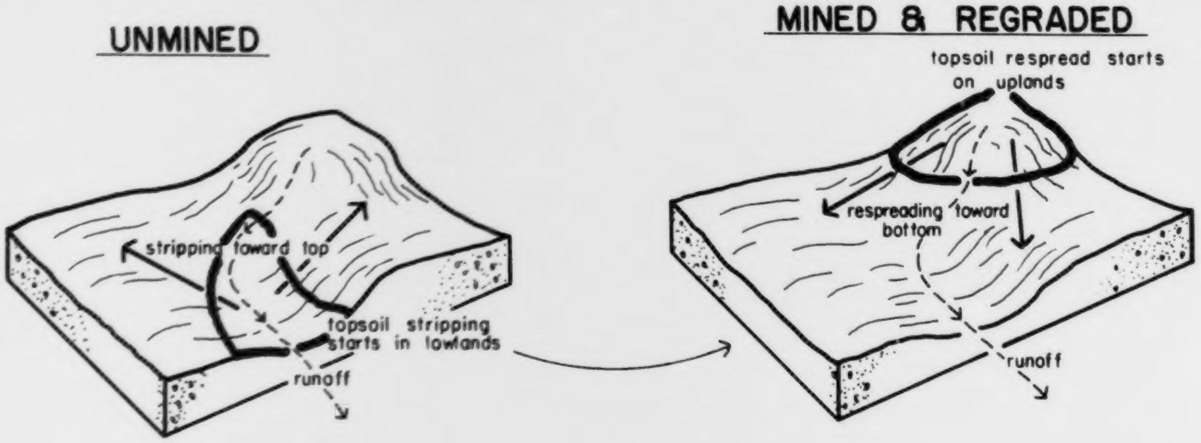
1982, Power et al 1976, 1978, 1979, 1981, Bauer et al 1976). In 1986 the North Dakota Public Service Commission approved new regulations allowing a lesser total respread thickness, based on regraded spoil quality. They found that as little as 24 inches of total suitable plant growth material (topsoil plus subsoil) may be sufficient to achieve 100% equivalent production over high quality spoils. These regulations are not applicable to prime farmlands. Despite research proving such respread depths are not necessary, a minimum 48 inches of soil is required to be respread for prime farmland reclamation. This requirement increases environmental disturbance, by requiring larger soil stockpile areas and water management facilities. In addition, it adds unnecessary earthwork costs.

Current North Dakota regulations require segregation of topsoil and subsoil for all lands mined. Topsoil is considered to be a combination of the A horizon and the dark-colored portion of the underlying B horizon. Topsoil at the Freedom Mine averages about 14 inches thick; in cropland and prime farmland it generally ranges from 10 to 20 inches. In heavily cropped areas, where conservation practices were not previously employed and erosion has taken its toll, topsoil has been found to range from less than six inches on hilltops to over six feet in drainages.

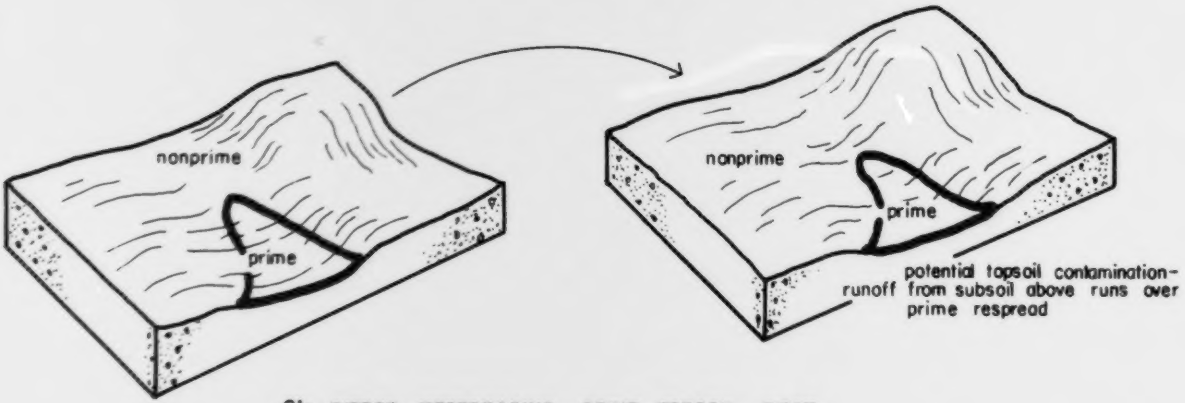
Subsoil is considered to be the underlying, lighter colored, B and C horizons, to a depth of five feet. In most croplands mined, subsoil has elevated levels of calcium carbonate, visible to heavy equipment operators in the field as white streaks of "lime". The stark color change between topsoil and subsoil makes it a fairly simple task for trained operators to successfully segregate these materials with tractor-scrapers.

Current rules allow the mixing of prime and nonprime subsoil, because of their similarity. Prime and nonprime topsoil, however, must be segregated from each other, based on the inherent assumption there are significant differences between prime and nonprime topsoil. As previously described, however, there is no significant difference between adjacent prime and nonprime topsoils in western North Dakota. Segregation of prime and nonprime topsoil results in increased environmental disturbance and costs. Where separate landowners are involved, or where no regraded areas are available yet for direct prime farmland respread, larger soil stockpile areas and water management facilities are required. Because there is no discrete break between prime and nonprime topsoils in the field, increased surveying and staking is required.

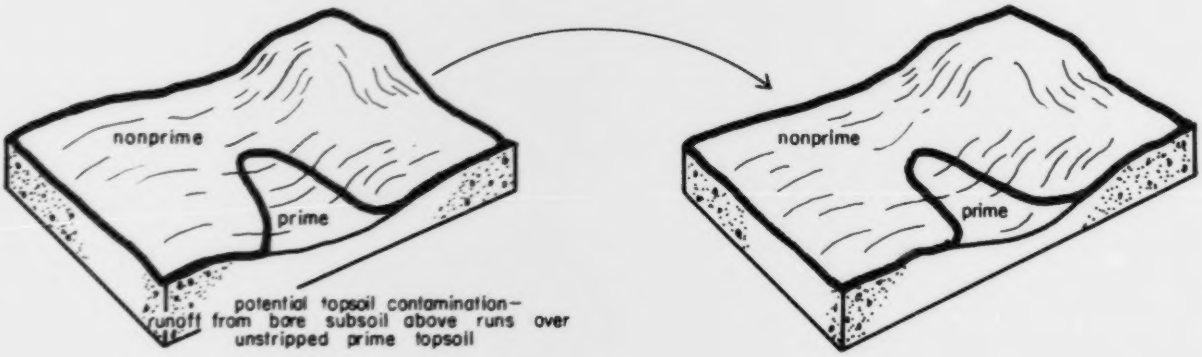
Potential for environmental degradation is increased significantly by prime/nonprime topsoil segregation. Normally, to affect proper water management, drainages are stripped of soil first. This reduces the possibility of runoff water draining off stripped, exposed subsoil areas from running over unstripped topsoil, lower in the landscape, resulting in contamination (Figure 3a). Reclaimed drainages are respread with topsoil last for the same reason (i.e., to avoid the possibility of runoff water from respread subsoil contaminating respread topsoil below). Prime topsoil is stripped from low drainages or swales, and must be replaced in a similar landscape position on reclaimed land. As prime and nonprime topsoil must be handled separately, operations are faced with two environmentally unsuitable alternatives: strip and respread prime farmland topsoil first, resulting in potential prime farmland topsoil contamination in the respread area (Figure 3b), or strip and respread upland, nonprime topsoil first, resulting in potential prime topsoil contamination in the area being stripped (Figure 3c).


UNMINED
MINED & REGRADED
topsoil respread starts on uplands
stripping toward top
respreading toward bottom
topsoil stripping starts in lowlands
runoff
runoff

3a. NORMAL OPERATIONS- TOPSOIL FROM LOW AREAS STRIPPED FIRST AND RESPREAD DIRECTLY ON RECLAIMED UPSLOPE POSITIONS, ELIMINATING POTENTIAL TOPSOIL CONTAMINATION BY RUNOFF FROM BARE SUBSOIL ABOVE.


nonprime
prime
nonprime
prime
runoff
potential topsoil contamination-
from subsoil above runs over
prime respread

3b. DIRECT RESPREADING PRIME TOPSOIL FIRST


nonprime
prime
runoff
potential topsoil contamination-
from bare subsoil above runs over
unstripped prime topsoil
nonprime
prime

3c. DIRECT RESPREADING NONPRIME TOPSOIL FIRST

FIGURE 3

Mixing prime and nonprime topsoil would eliminate the potential for environmental damage. In addition, it would reduce unnecessary additional stockpiles and related water management facilities. Staking and survey time would also be reduced. Because prime farmland soils are created largely as a result of erosion from above in the unmined landscape, such mixing during respread would more closely reflect premine conditions before intensive cropping accelerated soil losses. Richardson (1983) and the Land Reclamation Research Center (1988) recommended mixing prime and nonprime topsoils to enhance reclamation.

Because of conflicting regulations requiring the use of two different soil surveys, field identification of prime soils is often difficult, and sometimes totally inaccurate. The SCS Mercer County Soil Survey (SCS 1978) is used to determine the locations of prime farmland for separate handling during mining. This is required by both the North Dakota Public Service Commission and the Soil Conservation Service. The county soil survey is conducted at a scale of 1:20,000, and mapping for this survey is not performed at the detail required for soil survey maps for mining permits and operations (1:4,800). Consequently, enlarging the county soil survey, and overlaying it on the detailed soil survey map, reveals several discrepancies. For this reason, locations of prime farmlands mapped by the SCS may not correspond to those indicated on the detailed soil survey. As a result, mapped prime farmlands are often staked on hillsides, steep slopes adjacent to drainages, and on ridges having shallow soils. Stomberg (1985) found within the area mapped as prime farmland by the SCS, about 35% of the acreage was actually comprised of nonprime soils, and that for any particular landowner, nonprime soils may comprise from 22 to 91% of mapped prime farmlands. Using county soil surveys results in many prime soils being identified and handled as nonprime. When drainages are stripped as nonprime soil, and hilltops are stripped as prime soil, considerable confusion results in field operations.

Operations on Prime Farmlands

Actual handling of prime and nonprime soils is identical, except that prime topsoil is segregated from nonprime, as previously described. Special stakes are used to delineate stripping limits for prime farmland topsoil. During regrading operations, prime farmland landscapes are constructed. These regraded areas have plane to concave slopes less than six percent. This is not a regulatory requirement, but a permit condition, developed after examination of the nature of premining prime farmland landscapes. During soil stripping operations, if areas are available to respread stripped prime topsoil, it will be directly respread. If no areas are available, it will be stockpiled until a later date. If a favorable reclaimed prime farmland landscape is available, but no prime farmland is being stripped at the time, prime topsoil must be taken from a stockpile. Acreages of prime respread and stripping areas are rarely exactly the same, requiring stockpiling prime topsoil or opening up a stockpile to get more material. This results in construction of new stockpiles, or disturbance of otherwise existing stable stockpiles. Timing of regrading and stripping operations therefore becomes critical to reduce unnecessary disturbance, and more efficiently reclaim prime farmlands with prime topsoil.

Required respread depth for prime farmlands must be 48 inches, as previously described. Because prime and nonprime topsoils are segregated from each other throughout the entire mining and reclamation process, separate topsoil respread depths must be calculated. Currently, prime topsoil is respread 16 inches thick, and nonprime topsoil is respread 13 inches thick. There is some question regarding the wisdom of respreading deeper topsoil in the lowest part of the reclaimed landscape, and shallower depths on hills and slopes above (Richardson 1983). Natural erosional processes will eventually result in deeper topsoil in lower, reclaimed prime farmland areas. By respreading soils evenly, or even respreading a thicker amount on slopes and hilltops, overall reclamation would be enhanced. This is further reason to mix prime and nonprime topsoil.

Regulations require the same acreage of prime farmland be reclaimed as existed prior to mining. The acreage of regraded prime farmland landscapes far exceeds the acreage required for reclaimed prime farmland (Figure 4). If prime farmland is primarily a function of landscape position, rather than soil quality, the potential exists for a larger amount of reclaimed land to be classified as prime farmland several years from now. Schafer (1984) found an increase in agricultural land capability at several reclaimed sites in the Northern Great Plains, with improvement in many areas a result of constructing more favorable landscapes.

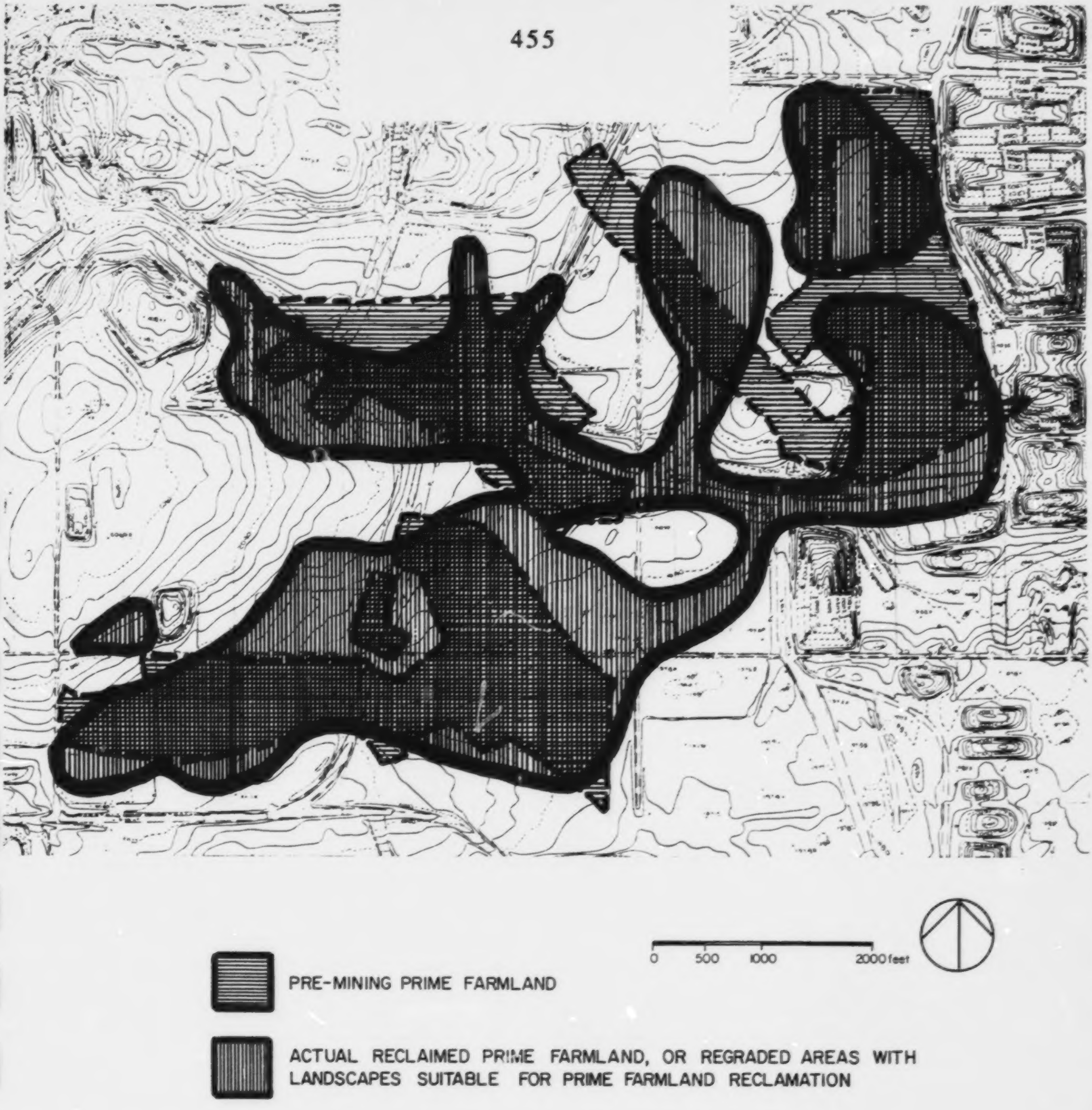
All reclaimed prime farmlands are mapped. Vegetative production was measured during 1988. This was an exceptionally dry year, with precipitation less than half of normal. Nonetheless, few differences were found between reclaimed prime and nonprime farmland, with regard to hay production. Productivity monitoring will continue for the next several years. To determine successful reclamation in North Dakota, prime farmlands are evaluated for three years, and nonprime lands for two.

Conclusions and Recommendations

In summary, prime farmland reclamation requirements are counterproductive, when applied to conditions in North Dakota. These include determination of prime farmlands based on county soil surveys, separate handling of prime and nonprime soils, separate respread depths for prime and nonprime topsoils, and a minimum 48" total soil respread depth. These requirements increase environmental disturbance and the potential for soil contamination. Costs are increased with no enhanced reclamation benefit. An opportunity to reduce erosion losses, by respreading soils evenly over the reclaimed landscape, is lost when prime topsoil must be respread more deeply in low reclaimed areas.

Two recommendations are provided to enhance reclamation, reduce environmental disturbance, and lower costs: (1) allow mixing of prime and nonprime topsoil; this will result in a more even respread over all reclaimed lands, and reduce stockpiling needs, and (2) allow the use of spoil quality to determine respread depths for prime farmlands, as it is currently being used for all other reclaimed lands to be returned to 100% productivity in North Dakota.

Current prime farmland regulations do not address site specific requirements of surface coal mining and reclamation in North Dakota. North Dakota surface mining regulations are adequate to protect all lands mined, including prime farmlands. Overlap and conflicts between Federal and State rules result in reduced environmental protection and increased costs. Proposed changes would enhance environmental protection and reclamation potential, and decrease costs.


0
500
1000
2000 feet
PRE-MINING PRIME FARMLAND
ACTUAL RECLAIMED PRIME FARMLAND, OR REGRADED AREAS WITH LANDSCAPES SUITABLE FOR PRIME FARMLAND RECLAMATION

CRITERIA FOR PRIME FARMLAND LANDSCAPES

— Slopes plane to concave
— Slopes less than 6%

Figure 4. Pre-mining prime farmland acreage vs. reclaimed prime farmlands and potential post-mining prime farmland landscapes on areas mined and regraded at the Freedom Mine.

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Possibilités de réutilisation et de réaménagement de mines abandonnées souterraines; considérations géologiques et environnementales [1]

Geological and environmental considerations in abandoned underground mine reuse and rehabilitation

par/by:
Dr. Daniel J. Boivin [2]

Résumé. Jusqu'à maintenant, beaucoup de recherche et de projets de restauration de sites miniers abandonnés partout à travers le monde ont été réalisés et la plupart d'entre eux portent en fait sur la récupération des terrains et la revégétation des sites dégradés. Or, cet article documente un aspect négligé de la réhabilitation de ces sites soit celui de leur reconversion en une autre vocation en étudiant les possibilités des excavations en tant que telles. Puisque les activités minières ont laissé en place de vastes espaces souterrains disponibles, ceux-ci peuvent vraisemblablement offrir un certain intérêt pour d'autres usages. Nous insisterons plus spécifiquement sur les possibilités et les contraintes reliées à ces excavations en matière de géologie et d'environnement. Parmi les réalisations rencontrées un peu partout dans le monde figurent par exemple la reconversion en réservoirs d'eau et d'hydrocarbures, en pépinières, en cultures de légumes et de champignons, en entrepôts de matières en vrac, en attraction touristique et même en installations industrielles.

Mots-clés: Réaménagement, mines abandonnées, conversion, excavations souterraines.

Abstract. Up to now, much attention has been devoted to the restoration of abandoned mining sites all over the world, with great emphasis on reclamation and revegetation techniques to restore the land to environmentally acceptable standards. In this paper, the reconversion possibilities of underground excavations are documented. With the availability of an underground empty space left at the end of the mining operations, the cavities might very well be of great interest for certain reuses. This paper describes the possibilities and the constraints offered by these excavations, with specific attention to geological and environmental considerations. Among the possibilities in use across the world are the conversion of old mines into water or oil reservoirs, dry goods storage, plant nurseries, vegetable and mushroom farms, tourist attractions and even industrial facilities.

Key-words: Rehabilitation, abandoned mines, conversion, reuse, underground excavations.

Problématique de la sécurisation et de la réhabilitation des sites

> "...the alternative of converting disused mines into underground storage plants seems to have been dismissed and the possibilities of the system have not been given the consideration that they deserve."
>
> WETTLEGREN, G. 1978 , p.9

La problématique de la réhabilitation des terrains miniers abandonnés ou en voie de l'être passe nécessairement par une analyse de la valeur de ces terrains. Cette valeur doit tenir compte de la localisation du site, de la superficie et de la topographie des lieux et des contraintes laissées sur place après l'abandon des travaux miniers. Au Québec, l'analyse des possibilités offertes pour ces sites a été faite brièvement pour environ 90% des sites miniers abandonnés. Seules les régions de la Côte-Nord et du Saguenay Lac St-Jean de même que quelques sites dispersés dans l'Outaouais n'ont pas encore été visités et évalués. Parmi les données et paramètres qui sont consignées dans la fiche d'évaluation ne figure pas une détermination précise des options qui s'offrent pour la reconversion éventuelle de ces terrains en une nouvelle vocation. Dans la plupart des cas éloignés géographiquement, la restauration s'impose comme mesure pour les parties en surface des terrains impliqués. Ce facteur d'éloignement justifie bien souvent cette option unique. Cependant, pour quelques sites situés plus près d'agglomérations urbaines, il est possible de considérer une véritable réhabilitation du site et plus spécifiquemment de songer à utiliser les volumes souterrains laissés à l'abandon à d'autres usages. Nous croyons que cette alternative est souvent négligée par simple manque d'expérience ou d'imagination (voir tableau 1). Plusieurs réalisations à l'étranger nous porte à croire que nous sous-estimons le potentiel de reconversion de ces sites. Nous croyons donc utile de rappeller quelles sont ces options et quelles contraintes y sont associées.

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[1] Paper presented at the conference Reclamation, A Global Perspective, held in Calgary, Alberta, Canada, August 27-31, 1989.

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Forme des excavations

Un des facteurs les plus importants à analyser en matière de réutilisation concerne d'abord la forme des excavations souterraines. On connaît deux types de travaux en souterrains soit les cavités minées et les réseaux de tunnels, galeries et puits.

Les possibilités offertes par chacun de ces types dépendent en premier lieu de la stabilité de ces ouvrages. Il va sans dire que des travaux partiellement effondrés ou dont le risque d'effondrement est élevé seront d'un faible intérêt. Ceci est lié tout d'abord aux risques élevés d'accidents lors de la remise en état, mais aussi au cours de la période d'utilisation de l'excavation. Mais surtout, l'instabilité des parois et plafonds entraîne des coûts exorbitants de soutènement et de rénovation qui nécessitent par ailleurs une expertise précise en génie minier. Le but recherché ici est de localiser et d'identifier des cavités ou des ouvrages encore solides qui pourront être aménagées au minimum de coûts.

Il est utile ici de remarquer que certaines utilisations du sous-sol ne se préoccupent pas autant de la forme des cavités que du volume impliqué (WETTLEGREN, 1978). Ainsi, dans certains cas, la forme des galeries et corridors souterrains peut représenter une contrainte alors que dans d'autres, il en est autrement. C'est le cas par exemple du stockage de liquides où la forme n'est pas un critère très important par rapport au volume. A ce moment, la présence d'obstacles dans les galeries pourraient nuire au libre écoulement et circulation des liquides dans les galeries. Aussi, la viscosité du liquide peut être retenue comme un paramètre à ne pas négliger; dans le cas de stockage de pétrole brut par exemple où la masse liquide est très visqueuse, il est possible que la circulation latérale ou verticale soit plus difficile dans d'étroites galeries alors que l'eau circule sans problème. De tels exemples de cavités souterraines sont présentes au Québec dans l'Abitibi, en Estrie, dans la région de Chibougamau et dans l'Outaouais.

Une ancienne mine souterraine de chromite située dans la municipalité de Black Lake (Estrie) fut transformée en réservoir d'eau. Ce réservoir sert comme volume d'eau disponible en cas d'incendie. En effet, il y a plusieurs années, la mine Bell a connu un incendie à son moulin. Cet évènement a éveillé les industriels locaux au risque de tout perdre leur investissement

TABLEAU 1
USAGES ACTUELS DE MINES OU CARRIERES SOUTERRAINES ABANDONNEES

FONCTION	EXEMPLES
caves à vin	carrières de Meudon (banlieue parisienne)
caves à fromages	carrières de Meudon (banlieue parisienne)
champignonnières	carrières de Meudon (banlieue parisienne)
	carrières West Winfield (Pennsylvania)
réservoir d'eau	Trondheim (Norvège)
réservoir d'hydrocarbures	Flaxenvik (Suède)
	May-sur-Orne (France)
archives (films, rubans magnétiques, livres, dossiers, disques, vidéos,...)	Hudson (New York)
entrepôts	Kansas City (Kansas)
usines	Kansas City (Kansas)
bureaux	Kansas City (Kansas)
ossuaires	catacombes de Paris (France)
habitats troglodytiques	Vallée de la Loire (France)
abris nucléaires	très répandu à travers le monde

sources: AUGHENBAUGH, N.B. (1974) et BREGEON, J. (1987)

et de menace de fermeture éventuelle de leur mine s'il ne prévoyait pas des mesures contre les incendies. Or, cette ancienne mine se situait à quelques centaines de mètres du moulin de la compagnie Lac d'amiante du Québec siutée en bordure de la route 112. A cause également de la différence d'altitude entre cette ancienne mine et le moulin situé plus bas, on s'est rapidement aperçu que la pression d'eau serait alors plus que suffisante pour alimenter le système de lutte contre les incendies du moulin.

Dans le cas du stockage d'hydrocarbures dans d'anciennes cavités minées, l'exemple de Flaxenvik en Suède retient tout particulièrement l'attention de même que l'ancienne mine de fer de May-sur-Orne près de Caen en France (voir figures 1 et 2). Dans les deux cas, des cavités laissées à l'abandon furent inspectées et jugées capables de recevoir des hydrocarbures.

En matière de forme des ouvertures, un intérêt particulier est également centré autour des mines souterraines dont les galeries et tunnels sont sub-horizontaux. Ces vastes espaces de passages et de piliers peuvent présenter des avantages pour plusieurs. La figure 3 montre justement une carrière souterraine convertie en usine.

Ainsi, à partir de galeries rectilignes abandonnées comme c'est le cas sous Paris (voir figure 4), on peut installer différents usagers dans les galeries. Les facteurs à retenir sont la stabilité des ouvrages, la hauteur des plafonds, la largeur des galeries, l'absence d'eau ainsi qu' une température ambiante acceptable.

Stabilité des ouvrages

L'intégrité des parois et des plafonds constitue une première exigence pour le réaménagement d'une cavité quelconque. Plusieurs méthodes éprouvées peuvent être envisagées pour corriger des problèmes locaux. Citons par exemple l'usage de gunnite ("shotcrete"), la pose de boulons d'ancrage ou de piliers additionnels, de cintres en acier et de grillages pour contrôler les chutes de blocs.

Un des problèmes rencontrés dans certains types de roches concerne le gonflement de minéraux argileux lorsque les parois sont exposées à l'oxygène de l'air. Ainsi, les roches contenant de la montmorillonite (argile) peuvent provoquer des éclatements et déstabilisation de parois. Certaines roches argileuses comme les shales peuvent également se déstructurer et s'effriter au simple contact de l'air. Dans ces deux cas, l'usage de gunnite projetée sur les parois fraichement écaillées ou dénudées permet de régler ce problème de façon permanente.

Hauteur des plafonds

En matière de hauteur des plafonds, un minimum de 2.44m est requis lorsque l'homme doit circuler dans ces cavités. Ceci est nécessaire afin de disposer de suffisamment de dégagement pour la pose du système d'éclairage. Il est préférable cependant (pour des questions d'ordre psychologique surtout) de privilégier des plafonds plus hauts.

Largeur des galeries

En ce qui concerne la largeur des corridors, on recherchera des galeries larges et rectilignes. Ainsi, les pièces créées offriront plus de flexibilité pour l'aménagement comme cela est le cas actuellement à l'usine souterraine Brunson à Kansas City. Cet aspect prend plus ou moins d'importance selon l'usage. Ainsi dans le cas des caves à vin, le stockage des bouteilles se fait directement dans les galeries en laissant simplement un passage au centre. La largeur des corridors sera aussi déterminante si l'on utilise des véhicules motorisés comme dans le cas des fermes de champignons où toutes les étapes de préparation exigent un transport de matières premières, du produit de la récolte ou de l'équipement d'entretien des lieux.

Absence d'eau

L'absence de venues d'eau dans les galeries est primordiale à plusieurs points de vue. D'abord, les galeries doivent être à sec pour permettre l'installation de machines et d'équipement à l'abri de la rouille et de l'inondation. Puisque beaucoup de ces appareils fonctionneront à l'électricité (tout combustible inflammable est à proscrire à cause du danger d'explosion), il est nécessaire que les conditions d'implantation soient sans eau. En deuxième lieu, le taux d'humidité doit être le plus bas possible à la fois pour le confort des usagers que pour les denrées et équipements qui y trouvent place. Un taux d'humidité trop élevé est d'ailleurs fort difficile à abaisser et impliquerait des coûts trop élevés en termes d'équipement de ventilation et de déshumidification.

Enfin, la présence d'eau peut endommager les aménagements intérieurs tels que murs intérieurs, parois, équipement de bureau et nuire au bon fonctionnement d'appareils tels que photocopieuses, dactylos, ordinateurs, téléphones et autres appareils électriques et/ou électroniques. La situation optimale à rechercher consiste d'une part à pomper l'eau qui s'infiltre et de la diriger dans le système d'égoûts installé; dans le cas toutefois où la quantité d'eau impliquée est très impor-

Figure no. 1
Coupe du dépot d'hydrocarbures de Flaxenvik, Suède
Cross-section of the Flaxenvik oil depot, Sweden

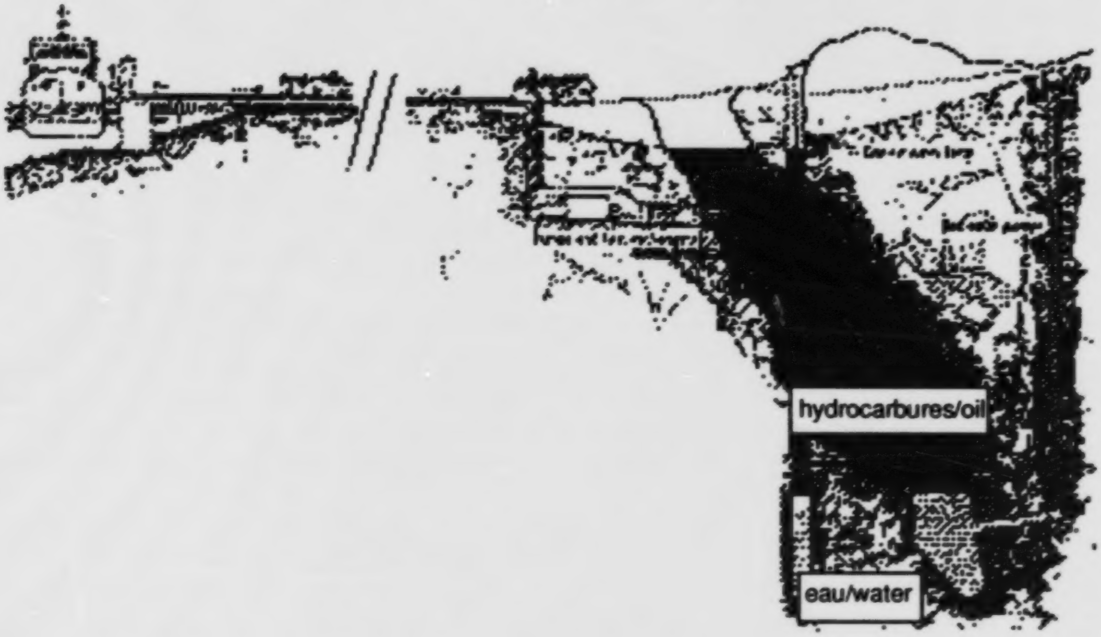
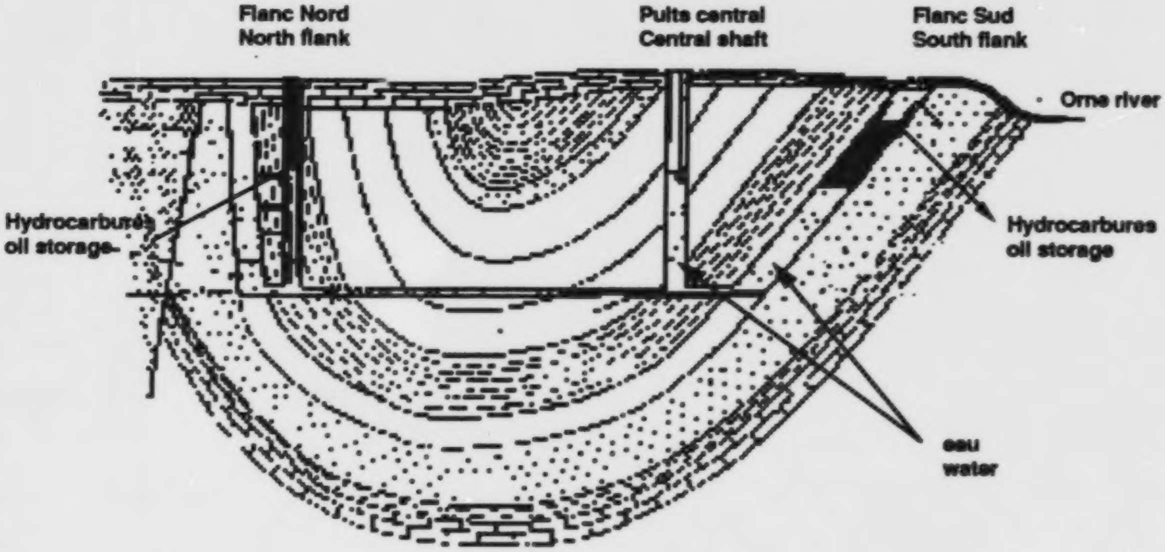

hydrocarbures/oil
eau/water

Figure no. 2
Vue en coupe de la mine de fer de May-sur-Orne, France
Cross-section of the May-sur-Orne iron mine


Flanc Nord
North flank
Puits central
Central shaft
Flanc Sud
South flank
Orne river
Hydrocarbures
oil storage
Hydrocarbures
oil storage
eau
water

source: MAURY, V. (1977)

Figure no. 3
Vue générale de l'usine souterraine Brunson, Kansas City, USA
General view of the Brunson underground plant in Kansas City, USA.

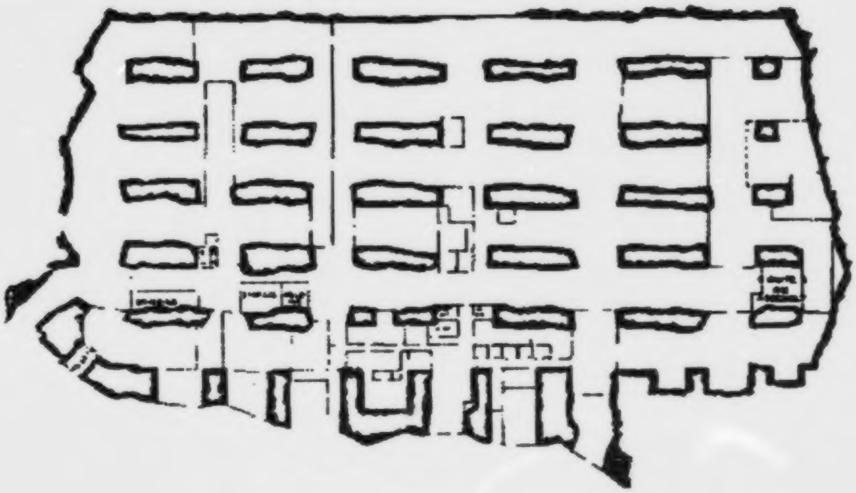
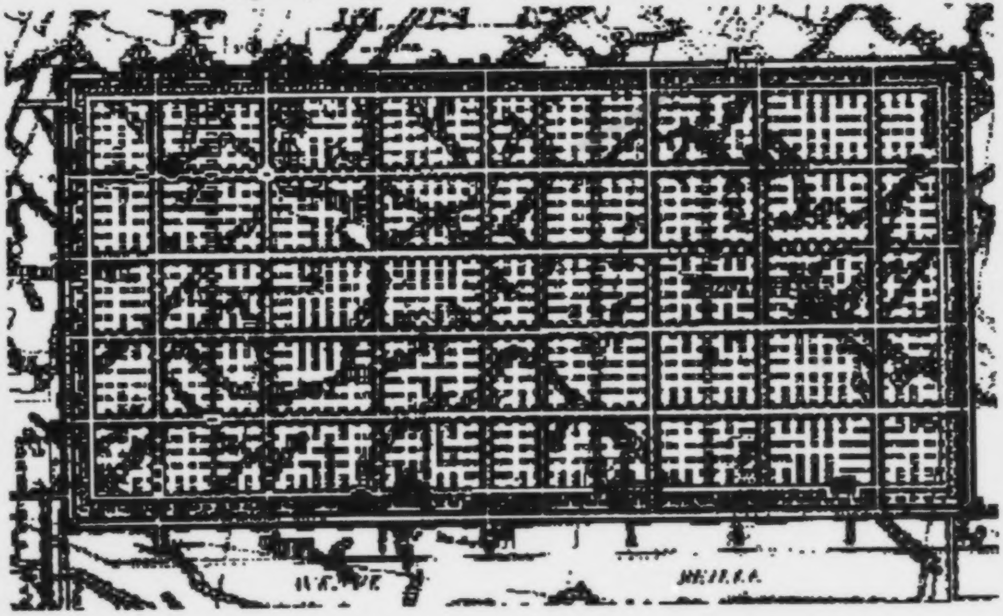


Figure no. 4
Pattern régulier de certaines carrières sous Paris, France
Regular patterns of certain quarries under Paris, France



tante, il est alors préférable d'installer des évacuateurs de type pluviaux qui seront distincts du réseau d'égoûts. Localement, il peut être avantageux de traiter les fissures et venues d'eau à l'aide de ciment ou de résines ("grouts"). Le traitement de l'ensemble des parois des cavités est par ailleurs souvent trop coûteux en soi et c'est l'usage de la cavité qui dictera les sommes économiquement acceptables qui devront être dépensés à ce chapitre (JACOBY, 1973, p. 98).

Stockage des hydrocarbures et principe de captation des eaux souterraines

Le principe de base qui autorise le stockage d'hydrocarbures dans le roc c'est-à-dire sans revêtement de béton ou d'acier dans les cavités repose sur le fait que les hydrocarbures sont plus légers que l'eau et ne se mélangent donc pas. La cavité doit donc d'abord se situer totalement en-dessous de la surface libre de manière à empêcher que les produits pétroliers ne migrent dans la nappe près de la surface (WETTLEGREN, 1978 et KELSALL, P.C. et al., 1973).

"C'est ainsi que le stockage des produits à tension de vapeur se fait à une profondeur telle qu'en tout point de la cavité la pression hydrostatique soit supérieure à cette tension de vapeur. De cette façon, les seuls mouvements de fluides possibles sont ceux de l'eau interstitielle de la roche encaissante vers la cavité, éliminant ainsi tout risque de fuite du produit à l'extérieur de la cavité vers les nappes".

PANTIN (1979), p.909

A partir de ces observations, il faut également noter qu'il existe à l'heure actuelle deux méthodes de stockage l'une appelée "à niveau d'eau fixe"(figure 5) et l'autre "à niveau d'eau mobile"(figure 6) (JANSSON, 1977). La méthode de stockage à niveau d'eau fixe implique que ce niveau est maintenu constant au fond de la cavité à l'aide d'un petit mur de béton autour d'un puits excavé dans le plancher de la cavité. Les eaux souterraines sont ainsi collectées dans ce puits puis pompées régulièrement en surface. L'espace inoccupé au-dessus du produit stocké est rempli d'un mélange d'air et de gaz. Cette méthode présente les avantages suivants:

- équipement de pompage et de nettoyage de dimensions réduites et donc moins coûteux;
- peu d'eau et d'émulsions eau/pétrole à pomper et à nettoyer.

Cette méthode est particulièrement indiquée pour les produits peu ou pas volatiles.

Figure 5
Principe général de stockage d'hydrocarbures à niveau d'eau fixe
Fixed water bed method in underground oil storage

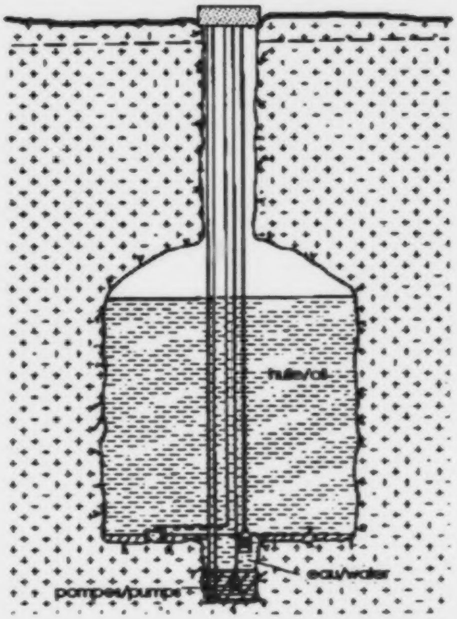
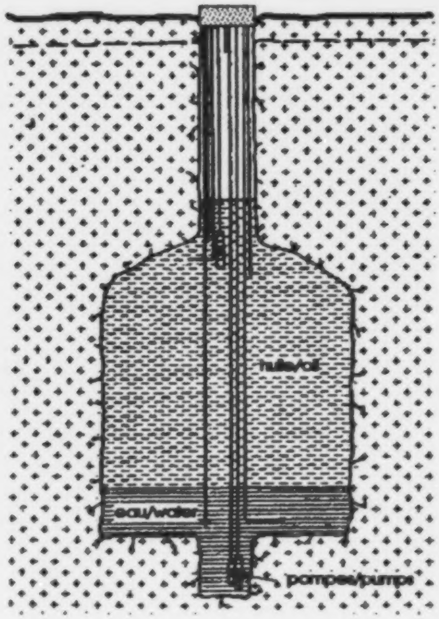


Figure 6
Principe général de stockage d'hydrocarbures à niveau d'eau variable
Mobile water bed method in underground oil storage



La méthode de stockage à niveau d'eau mobile implique que le produit stocké flotte au-dessus de l'eau. Le niveau supérieur du produit stocké est maintenu le plus près possible du plafond de la cavité pour restreindre la quantité de gaz produit. Ainsi, le niveau de l'eau varie selon le volume de pétrole dans la cavité. Cette méthode est de moins en moins utilisée aujourd'hui car elle requiert un équipement considérable pour pomper et nettoyer l'eau.

Des recherches récentes conduites par la firme GEOSTOCK ont également montré l'importance de reconstituer le niveau de la nappe au-dessus de la cavité. L'excavation et l'opération de cavités semblables provoque un rabattement localisé de la nappe; l'influence de ce rabattement peut même être importante si l'on considère que ces cavités sont situées en profondeur. Il faut donc réinjecter l'eau pompée au-dessus de la cavité afin de rétablir la pression hydrostatique et ainsi créer une boucle pompage-réinjection-captage. Ce système dont la pression requise se situe à 1 bar par tranche de 10 mètres, permet ainsi d'éliminer tout danger de contamination de la nappe.

Notons en dernier lieu que le stockage prolongé d'hydrocarbures tel le pétrole brut entraîne une certaine accumulation de matières visqueuses au fond des chambres. MOBERG (1977) rapporte une accumulation de 50 cm après 15 ans d'opération. Puisque l'enlèvement de cette boue est extrêmement coûteux, il est préférable de voir à ce que ceci ne gêne pas les opérations. Il en va de même pour les chutes potentielles de roc provenant des murs ou du plafond.

> "At the present time, the excavation of new caverns (is) estimated to cost between $U.S. 5.00 to $U.S. 7.00 per barrel......It is interesting to note that the provision of storage in surface-located steel tanks is currently estimated to cost approximatly $U.S. 11.00 per barrel".
>
> MOBERG (1977), p. 151

Bien que ces chiffres fort éloquents militent en faveur du stockage en souterrain, il existe encore bien peu d'installations de ce genre en dehors des pays scandinaves. JANSSON & SODERBERG (1981) se sont interrogés sur les raisons pourquoi certains projets ont été abandonnés ou reportés indéfiniment; ces renseignements nous sont particulièrement utiles, car ils permettent de bien identifier les obstacles à surmonter dans l'avenir. Ces raisons sont:

- le prix du pétrole trop élevé;
- des coûts de construction trop élevés;
- le manque de capital;
- des problèmes économiques dans le pays;
- des problèmes politiques dans le pays
- des raisons politiques diverses;
- la baisse de la demande en espaces d'entreposage;
- des oppositions locales au projet;
- en attente d'une décision quelconque;
- des investigations préliminaires mal conduites.

Les installations de stockage en souterrain présentent également des avantages en matière d'entretien. Ainsi, les coûts de chauffage des produits stockés l'hiver est évité et des économies importantes peuvent ainsi être réalisées à ce chapitre. Notons toutefois que les produits pétroliers stockés sont légèrement chauffés pour améliorer leur fluidité. L'exposition aux rigueurs du climat à l'extérieur entraîne également des coûts associés à l'usure, à l'oxydation, etc.: il faut par exemple remplacer du matériel (canalisations, pompes) et peinturer les réservoirs. Sous terre, l'opération et l'entretien des cavités et de l'équipement associé représentent entre 1/3 et 1/5 des coûts d'installation de mêmes volumes situés en surface. Tous ces chiffres militent en faveur du souterrain surtout si l'on considère le coût du terrain requis pour l'entreposage en surface et l'inesthétisme de la plupart de ces installations de surface (voir figure 7). En guise de rappel, les critères les plus importants sont:

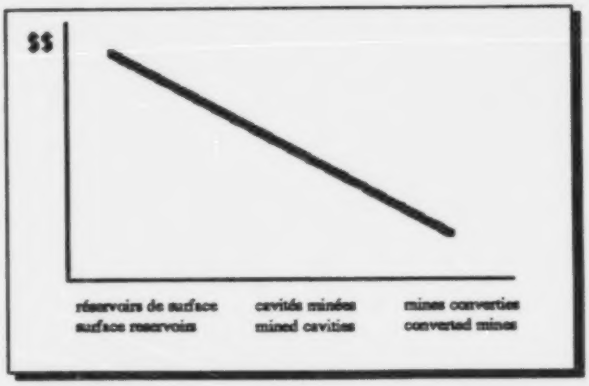
-la cavité doit être en-dessous du niveau de la nappe libre

-le projet de stockage n'est économiquement rentable que pour 100,000 m³

-l'excavation doit être située près des marchés ou d'installations portuaires

-les volumes disponibles ne doivent pas être situées à trop grande profondeur à cause des coûts de pompage requis.

Figure 7
Coûts approximatifs comparés de construction de réservoirs d'hydrocarbures
Gross comparison of cost for large underground oil storage installations



Localisation des mines souterraines

Le facteur qui limite considérablement la réalisation des travaux de reconversion d'excavations souterraines est sans aucun doute l'éloignement des sites des centres urbains. Ce problème semble moins important lorsqu'on s'attarde cependant aux excavations minières qui sont encore en exploitation ou qui ont fermé depuis peu. En effet, dans ces cas-là, de petites villes se sont développées autour des gisements qui sont exploités depuis longtemps comme c'est le cas pour l'amiante dans la région de Thetford Mines/Black Lake. Le facteur éloignement peut constituer un facteur intéressant cependant dans le cas du stockage de produits toxiques, de déchets industriels ou encore de résidus radio-actifs. Il en est de même pour les stockages de haute sécurité comme c'est le cas dans l'état de New York où différentes archives sont entreposées sous terre. Dans ce dernier cas, c'est la fréquence à laquelle on doit accéder aux produits stockés qui influence sur la distance considérée acceptable entre ce produit et le client.

Aspects énergétiques

L'intérêt des cavités souterraines est particulièrement marqué pour les questions énergétiques. En effet, le sous-sol bénéficie de conditions doublement intéressantes à ce chapitre. En premier lieu, la masse rocheuse représente un "isolant" contre les basses températures l'hiver, mais aussi contre les chaleurs de l'été. La masse rocheuse connaît également une température et une humidité constantes durant toute l'année. Ainsi pour une cavité située à une cinquantaine de mètres sous la surface, la température intérieure sera de l'ordre de 4 à 10°C pour notre climat continental tempéré. L'humidité y variera de 50 à 90% selon les quantités d'eau qui s'y infiltrent et la période de l'année (pénétration de l'air chaud extérieur qui condense sur les parois froides de la roche). Ainsi, en matière de chauffage, les quatre thermomètres de la figure 8 comparent deux espaces l'un en surface et l'autre souterrain. La figure montre en premier lieu que, durant l'hiver, l'amplitude à chauffer n'est que de 10°C en souterrain alors qu'elle peut être de 25°C en surface. Durant l'été, la situation est identique sous terre et on doit chauffer les 10°C nécessaires au confort des usagers alors qu'il faudra climatiser un édifice en surface.

Plusieurs auteurs (SERBANESCU et al. (1982), BOIVIN (1985)) ont vérifié l'affirmation que la température du roc à quelques dizaines de mètres de la surface approchait la température moyenne annuelle de l'air. La température qui règne à l'intérieur des cavités excavées est déterminée d'abord par le gradient géothermique qui est approximativement de 1°C/100 mètres (avec quelques variantes selon le type de roches traversé) et par l'apport d'air frais provenant de l'extérieur (ventilation). Afin de ne pas enrayer les avantages de chauffage naturel qu'offre le gradient géothermique, on doit prendre soin de réchauffer l'air extérieur. SERBANESCU et al. (1982) ont mesuré par exemple un accroissement adiabatique de la température qui descend dans le puits de l'ordre de 2.9°C pour 304.8 m ce qui s'apparente nettement aux données accumulées dans la littérature.

Discussion et conclusion

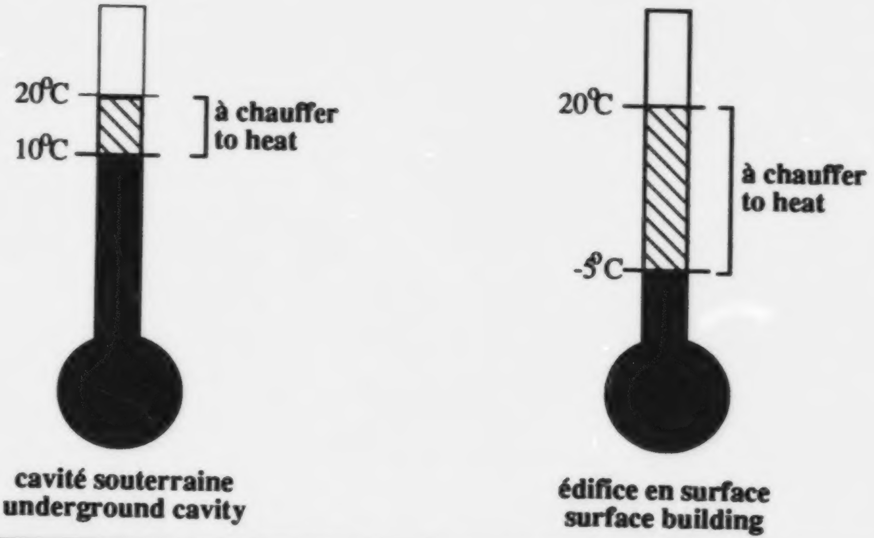
L'examen des différentes réalisations un peu partout à travers le monde a montré que la réhabilitation d'excavations souterraines est non seulement possible techniquement et économiquement, mais aussi souhaitable pour des questions environnementales. L'intérêt le plus marqué réside dans le fait que les travaux de réhabilitation ainsi que les sommes nécessaires afin de remettre en état des sites pollués et inesthétiques sont intégrés aux sommes investies pour l'aménagement d'un site productif. Ainsi, la conversion d'une carrière ou d'une mine dépasse la simple restauration qui doit suivre la fermeture d'un site semblable. On peut désormais envisager d'utiliser ces espaces pour leurs qualités intrinsèques. En 1973, JACOBY (1973 p. 92) écrivait déjà à cette époque:

> "The time is rapidly approaching when the cavity created during mining operations will be of more value than the mineral extracted".

L'expérience des carrières souterraines de Kansas City qui fut si bien décrite par STAUFFER (1972) mérite une attention toute particulière puisque les exploitants se sont vite aperçus que les espaces qu'ils créaient au fur et à mesure de la progression souterraine prenaient une valeur indéniable. A tel point qu'on a constaté un changement radical dans la façon dont on disposait les chambres et piliers (voir figure 9). D'un pattern irrégulier, on a développé des alignements plus ordonnés permettant par la suite d'aménager et de louer ces espaces comme entrepôts, usines et mêmes bureaux. Les exploitants rapportent aujourd'hui qu'ils font plus d'argent en location qu'avec la vente des matériaux extraits. Et l'exploitation continue afin d'étendre les superficies souterraines disponibles.

Figure 8
Demandes d'énergie comparées en hiver et en été entre des installations souterraines et de surface
Comparison of energy requirements in winter and summer for underground and surface installations

Situation d'hiver
Winter conditions


20°C
10°C
à chauffer
to heat
cavité souterraine
underground cavity
20°C
-5°C
à chauffer
to heat
édifice en surface
surface building

Situation d'été
Summer conditions

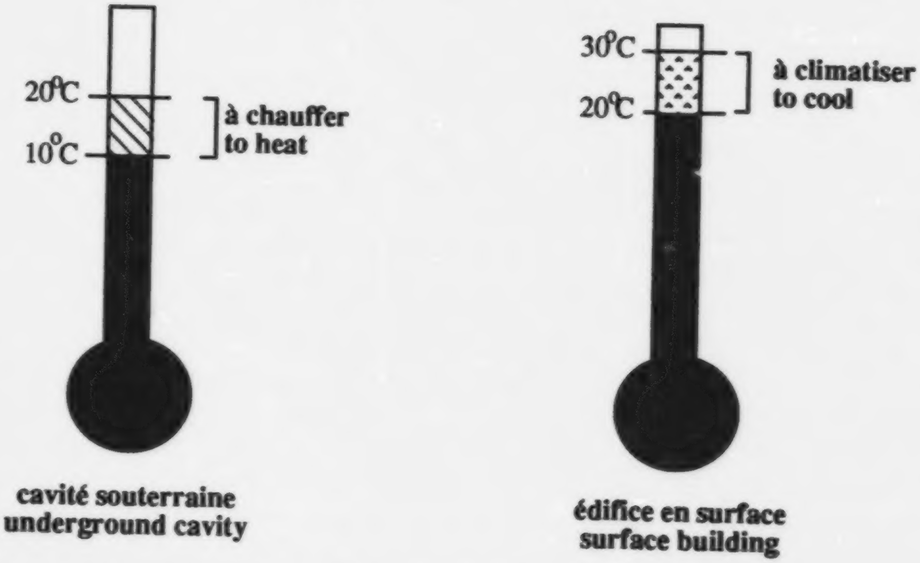
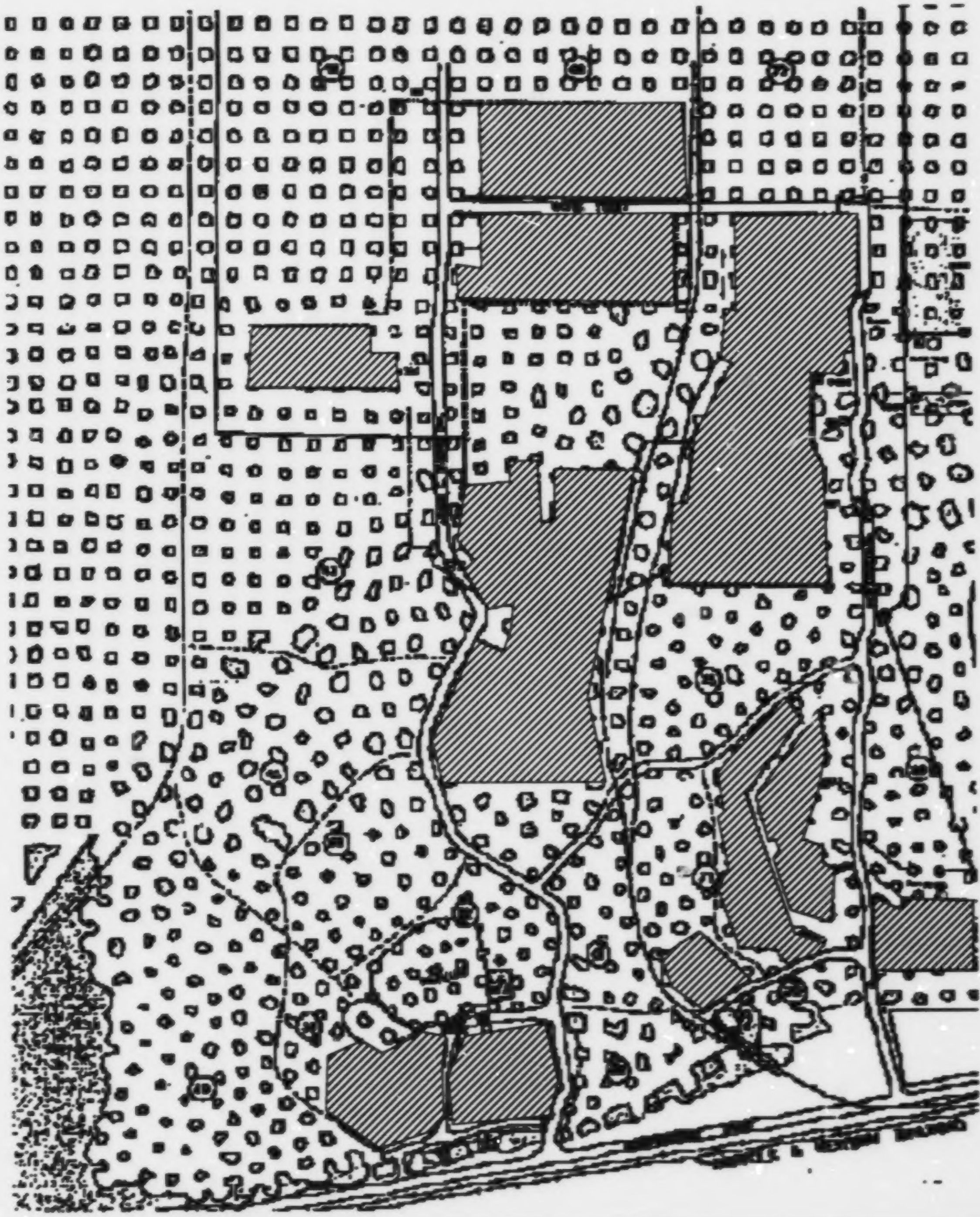

20°C
10°C
à chauffer
to heat
cavité souterraine
underground cavity
30°C
20°C
à climatiser
to cool
édifice en surface
surface building

TABLEAU 2
QUELQUES CARRIERES ET MINES SOUTERRAINES RÉAMENAGÉES

Installation	Superficie/volume	Mine/carrière	Lieu
Inland Underground Facilities Inc.	2,640,500 pi. carrés entrepôts:2,550,000 pi. carrés usines: 86,400 pi. carrés archives:4,100 pi. carrés	carrière	Kansas City (Kansas)
Mid-continent Underground Storage Warehouse	860,000 pi. carrés entrepôts:860,000 pi. carrés	carrière	Loring (Kansas)
Downtown Industrial Park Co.	1,116,000 pi. carrés entrepôts:1,116,000 pi. carrés	carrière	Kansas City (Missouri)
Underground Storage Inc.	799 000 pi. carrés entrepôts:599,000 pi. carrés usines:200,000 pi. carrés	carrière	Kansas City (Missouri)
U.S. Cold storage Corporation	200,000 pi. carrés entrepôts:200,000 pi. carrés	carrière	Kansas City (Missouri)
Brunson Instrument Co.	140,000 pi. carrés usine:140,000 pi. carrés	carrière	Kansas City (Missouri)
J.C. Nichols Company	125,000 pi. carrés entrepôts, usines et bureaux:125,000 pi. carrés	carrière	Kansas City (Missouri)
U.S. Government warehouse	2,600,000 pi. carrés	carrière	Atchison (Kansas)
The Security Terminals Warehouse	n.d.	carrière	Springfield (Missouri)
The Ozark Terminal Warehouse	n.d.	carrière	Neosho (Missouri)
Butter County Mushroom Farm	n.d.	mine	West Winfield (Pennsylvanie)
Géomines/May-sur-Orne	5,000,000 m 3	mine	May-sur-Orne (France)
Anrok Materials	1,500,000 pi. carrés	carrière	Kansas City
Midwest Pre-Cote	6,000,000 pi. carrés	carrière	Kansas City
Pixley	n.d.	carrière	Overland
Pixley	4,500,000 pi. carrés	carrière	Champagne
Mine Greenshields	n.d.	mine	Black Lake (Québec)

n.d.: pas de données
source: BENNETH-SMITH, L. (1977), EARLEY, F. (1968), HUGHES, D.C. & V.J. RYAN (1980), PANTIN, C. (1979).

Figure 9
Carrières réaménagées de Kansas City, Missouri
Use of abandoned quarries in Kansas City, Missouri



La préparation d'une cavité pour son réaménagement doit passer par deux étapes préliminaires qu'il est bon de résumer ici.

1. Investigation géotechnique

Une visite des lieux doit d'abord être faite afin de déteminer la qualité et la stabilité des excavations abandonnées. Différents tests seront effectués pour quantifier la résistance des piliers. Des photographies seront prises afin de localiser les endroits qui nécessiteront des travaux de soutènement. De cette manière, l'ingénieur minier sera en mesure d'estimer correctement où et combien de boulons d'ancrage, de cintres d'acier, de béton projeté seront requis et les coûts associés à ces travaux de comfortement.

2. Construction d'un modèle tridimensionnel

Plusieurs auteurs ont mentionné la nécessité sinon l'utilité de construire un modèle en trois dimensions des cavités abandonnées. Cette mesure permet entre autres de bien visualiser les volumes disponibles et leur position respectives, mais aussi de bien planifier le comportement et l'affectation des volumes. Il permettra de faire des choix plus éclairés et aussi d'économiser des sommes importantes en travaux supplémentaires. On oublie souvent aussi que le travail dans de telles excavations abandonnées présente un danger certain pour les mineurs qui y retourneront; c'est ainsi qu'une bonne connaissance des anciens puits, cheminées et chutes de minerais seront une mesure de sécurité très importante pour les futurs travaux.

Le survol rapide des possibilités et des contraintes offertes par les cavités minées abandonnées (ou en voie de l'être) nous montre la voie à suivre pour faire face à la fois aux exigences environnementales de plus en plus sévères et les coûts faramineux des travaux requis. La seule véritable contrainte réside probablement uniquement dans notre vue trop restreinte des solutions envisageables.

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An Overview of Two Decades of Regulation on Surface Coal Mining and Reclamation in North Dakota[1]

by

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Abstract. In North Dakota, coal (lignite) production and utilization methods have changed considerably since the first commercial coal mine was opened in 1873. Surface mining was started in 1919 and became the exclusive method of coal recovery by 1966. The number of coal mines, mostly small underground operations, declined from an all time high of 320 in 1940 to the current 10 active surface mines. But coal production has increased steadily, reaching 28 million tons in 1988. Today, 78% of North Dakota lignite is used for electrical generation, 20% for synthetic gas production, and the remainder as domestic and commercial fuel. Environmental regulation of North Dakota's lignite industry began in 1969 when the state passed its first mining and reclamation law. Reclamation requirements at that time were limited to topping and seeding the spoil peaks. Since then, the reclamation laws and rules have increased significantly in their scope and stringency and have had a profound effect on the quality and usefulness of lands following mining disturbance.

Additional Key words: history of mining, lignite, impacts of mining

Introduction

North Dakota has the largest lignite coal reserves in the United States. These reserves, estimated at 600 billion tons (Burr 1954), are mainly in the western part of the state, in the Tongue River and Sentinel Butte formations. The lignite bearing area in North Dakota covers about 28,000 square miles.

In 1988 approximately 28 million tons of coal were mined from the 10 active mines in North Dakota. The state's lignite industry presently employs about 18,300 people and produces an estimated annual total business volume of $988 million (North Dakota Lignite Council 1988).

Lignite is a dark brown low-grade coal that is softer than ordinary bituminous coal. It is characterized by a relatively high moisture content (averaging about 37%), low heating value (about 6800 BTU), moderate ash content (6-7%) and low sulfur content (about 0.6%) (Burr 1954). Presently about 78% of North Dakota lignite is used for electrical generation, 20% for synthetic gas production, and the rest for domestic and commercial fuel and charcoal briquetting.

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Although lignite mining is very important to the economy of North Dakota, its negative impacts to the environment and to the usefulness of land can be drastic. Therefore, in order to protect the environment from the harmful effects of mining, the state legislature passed its first reclamation law in 1969. This law was amended and changed several times, including modifications related to passage of the federal Surface Mining Control and Reclamation Act of 1977.

The objectives of this paper are to discuss the history and importance of coal development in North Dakota, and to describe how the development of an environmental regulatory program has led to mitigation of many of the adverse environmental impacts of mining in the state.

History Of Mining In North Dakota

The use of North Dakota lignite as a fuel source was first recorded in the journals of the Lewis and Clark expedition. Lignite was used to fire a blacksmith's forge during the winter of 1804-5 at Fort Mandan, near the present town of Washburn. During the 1850s and 60s, steamboats that navigated the Missouri River occasionally used lignite as fuel because of scarcity of wood in some areas along the route. Later, during the 1860s and 70s, military posts within present North Dakota experimented with lignite, but its use was limited because the posts originally lacked stoves adapted to burn it. Fort Stevenson was the only post that relied heavily on lignite. By the late 1870's civilian contractors supplied much of the lignite.

In 1873, Dennis Hannifan and John S. Warn formed the first coal company in North Dakota near Sims, about 30 miles west of Bismarck. The following spring they were driven off by Indians, and the mine remained inactive until the early 1880s when it was developed by the Northern Pacific Coal Company (Oihus 1978). According to the earliest official record, annual lignite production in North Dakota reached 35,000 tons in 1884 (Burr 1954). Many more mines were opened in the 1880s and 90s, generally near towns and villages along the railroads. Most of these mines were small operations but some, like the Baby Mine near Sims and the Mouse River Coal Company's Davis Mine northwest of Minot, were relatively large. Each of these mines at its peak produced about 100 tons of lignite per day (Oihus 1978).

Underground mining was the predominant method until the 1920s and 30s. It was usually done by the room and pillar method, in which coal was mined in blocks called rooms and wooden pillars were left to support the roof. Underground cutting machines and blasting were used as early as the turn of the century (Oihus 1978).

One of the largest lignite producers around the turn of the century was General W.D. Washburn's Wilton Mine. It produced 115,340 tons of lignite in 1910, over 25% of the state's production, which sold for $1.50 per ton at the mine. Besides supplying heating fuel for a large area, the Wilton Mine also operated a power plant that supplied power to the mine and the town of Wilton (Oihus 1978).

During the depression years of the 1930s, the number of small mines increased as farmers began mining lignite as an alternate source of income. The number of coal mines in North Dakota peaked at about 320 in 1940 (Dahlberg et al 1984).

An important change in North Dakota's lignite industry began in the 1920s when the steam shovel facilitated relatively easy removal of overburden, and made strip mining feasible on a large scale. There were 12 strip mines operating in 1920 . The number increased to 69 by 1929, and by 1939 there were more surface than underground mines in North Dakota (Oihus 1978). Strip mines were more efficient, less labor intensive, and generally safer than underground mines. However, their impacts on the environment were extensive.

Lignite markets changed during the 1940s as households began to switch from coal to natural gas and fuel oil. By 1948, about 65% of the state's coal was used to generate electricity (Oihus 1978). This market shift set the stage for the present era in North Dakota mining in which a few large scale strip mines provide fuel for huge electrical generating plants. By the end of the 40s only about 100 commercial mines remained; by 1960 the number had been reduced to fewer than 50, and by 1980 to 12 (Dahlberg et al 1984).

Large electrical generating plants were constructed in North Dakota beginning in the 1960s. Most of these are "mine-mouth" operations; that is, the generating plants are located near the mines that supply their fuel. During the 1970s and 80s the Great Plains Gasification Project was initiated near Beulah. This resulted in construction of a coal gasification plant which began production in June, 1984, and presently utilizes about five million tons of lignite annually, supplied by Coteau Properties Company's Freedom Mine.

Environmental Impacts of Mining

The first finding of the North Dakota law governing surface mining and reclamation (Section 38-14.1 NDCC) states that "many surface coal mining operations may result in disturbances...that adversely affect the public welfare by diminishing the utility of land." It has been estimated that about 7000 acres were strip mined in the state prior to enactment of the first reclamation law in 1969 (Hagen 1974). The majority of this acreage was used as cropland or rangeland prior to mining. The disturbances caused by strip mining reduced the utility of this land by wasting the nutrient rich topsoil, and by leaving spoil piles in place of what was once productive agricultural land.

Besides reducing the productive capacity of land, surface mining caused other negative environmental impacts. The spoil piles were steeply sloped and often could not support much vegetation. Erosion of the spoil piles led to water and air pollution and to deposition of undesirable sediments on nearby areas.

Research on the potential for reclamation of strip mined lands in North Dakota has been conducted since the early 1960s. The earliest efforts were concerned with reestablishment of grassland on spoil areas. Through the 1970s and 80s major advancements have been made through the efforts of various universities and research centers within the state. In fact, reclamation research has been a forerunner of much of the state's important legislation controlling the environmental impacts of mining.

Regulation of Mining

The North Dakota legislature passed laws regulating mining as early as 1907. These early laws dealt mainly with licensing, mine safety, and the prohibition of child labor in the mining industry. Since mining operations were relatively small and did not affect a large portion of the state, control of the environmental impacts of mining did not generate much public concern.

In the 1960s, however, public concern was aroused by the unreclaimed spoil piles left by the new large scale strip mines.

In 1963, the state legislature ordered a study of reclamation methods. This study concluded that no legislation was necessary at that time (Hagen 1974). The legislature passed another resolution in 1967 to investigate the need for reclamation of mined lands and to recommend appropriate legislation. This resolution resulted in enactment of the first reclamation law in North Dakota which was passed during the 1969 legislative session and became effective January 1, 1970.

Regulatory Program Development

The 1969 Law

The policy of the 1969 reclamation law was to provide for reclamation of affected lands to encourage their productive use. This law required each operator of a coal mine, where overburden depth exceeded ten feet, to obtain a permit. It designated the Public Service Commission as the agency responsible for the implementation and enforcement of the provisions of the law and provided for inspections to ensure compliance. The operator was required to submit a bond of $200 per acre to ensure reclamation in the event of permit revocation.

The law required the operator to strike off the tops of the spoil peaks to a minimum width of 35 feet for pastureland or 24 feet for afforested land, with peaks and ridges not to exceed 25% slope for cropland (unless the original grade was greater). It also required the operator to submit a reclamation plan based on the advice and assistance of the State Soil Conservation Committee, the State Game and Fish Department, and other agencies and individuals having experience in reclaiming mined lands. This plan had to designate which areas would be reclaimed for forest, pasture, cropland or other uses. Affected lands were required to be planted with appropriate seeds, plants or cuttings as approved by the Commission. Areas failing to support plant growth after initial planting had to be planted again.

The 1969 law was an initial step toward requiring coal mine operators to restore affected lands to the agricultural or other uses that existed prior to mining. Lands reclaimed under this law often became more useful than unreclaimed spoil piles. However, the success of reclamation was highly dependent on the physical and chemical properties of the spoil. For example, the glacial till spoil material at the Velva Mine in Ward County, being relatively low in sodium and salts, could be revegetated fairly easily. Therefore, grading required by the law made it possible to harvest hay or crops from the flattened spoil peaks, and thus made the land more useful. However, at other locations such as the Larson Mine in Burke County the sodic, clayey textured spoil made successful revegetation of affected areas nearly impossible. In fact, grading may have been counterproductive because it eliminated the shelter provided between the spoil peaks for wildlife.

The grading and seeding required by the 1969 law helped somewhat to stabilize the spoil piles and thereby reduced attendant air and water pollution. However, no containment or monitoring of runoff was required at that time.

The 1973 Law

Revisions made to the law in 1971 included a requirement that the operator obtain the landowner's preference for reclamation. But the next major changes to the law occurred in 1973: the operator was required to grade affected lands to approximate original contour (except for final cuts), remove all topsoil up to a depth of two feet prior to mining, and respread it after regrading of the spoil was completed. These changes greatly improved the usefulness of reclaimed lands.

The new grading requirements led to the elimination of the steep slopes (unless they existed prior to mining) that were an accepted consequence of mining prior to 1973. The requirements also led to a higher level of agricultural capability by increasing the proportion of the land that could be used for crop or hay production.

The requirement to save and respread topsoil greatly increased the potential for plant establishment on reclaimed areas. Power et al, (1974) found that as little as two inches of topsoil markedly increased vegetative establishment and production. Forage and crop yields on reclaimed lands respread with 12 inches of topsoil were found to be even better, with yields occasionally approaching premining levels (Doll et al 1983).

The 1973 law prohibited mining in certain areas where reclamation would be impossible or mining would imperil the welfare of the state. The operator was required to impound or otherwise treat all runoff water prior to discharging it from the minesite. This helped to reduce water pollution and sedimentation on agricultural lands. The law also required public notification of permit application. The amount of bond required was also increased at this time.

Important effects of the 1973 law were that reclaimed mined lands became nearly as useful and productive as they had been before mining, and many of the adverse environmental impacts of mining were confined to the minesite. This was especially true of those areas with good quality underlying spoil. It is important to remember that several major electrical generating stations had recently come on line or were being constructed at this time and, consequently, mining operations were becoming larger than ever before.

Another important result of the 1973 law was the creation of the Reclamation Division of the Public Service Commission. The Commission, with funds appropriated by the legislature, hired Dr. Edward J. Englerth as full time reclamation inspector. Subsequently, the Reclamation Division under the directorship of Dr. Englerth employed a multidisciplinary staff with expertise in geology, ecology, agricultural sciences, engineering and other disciplines in order to administer the ever more comprehensive regulatory program. The Reclamation Division was charged with reviewing permit applications, recommending and formulating programmatic changes, and conducting mine inspections to ensure compliance with the reclamation law.

The 1975 Law

The reclamation law was again revised in 1975. Perhaps the most important part of the 1975 law was its intent: "to restore mined areas designated for agricultural purposes to the level of inherent productivity equal to or greater than that which existed in the permit area prior to mining."

This declaration of intent had important ramifications to both the mining industry and the Commission. How is the level of inherent (premining) productivity defined? How can it be proven that this level has been restored after mining? The 1969 law required only that the land be graded, seeded, and if necessary reseeded. The 1973 law was more comprehensive but its only requirements for release of operator liability were to reclaim the land according to its approved plan to the satisfaction of the Commission. The 1975 law now required the operator to restore the land's premining level of productivity.

However, the question of how to define premining productivity and to prove that it had been restored after mining was largely left unanswered in the 1975 law. The operator was required to have a soil survey completed by a professional soil classifier prior to any mining disturbance. This survey had to consist of a map identifying soil types and topsoil and subsoil depths, and a report giving soil volumes and describing the chemical and physical characteristics and other properties of the soil materials.

The operator was required to: a) remove both topsoil and subsoil to a total depth of 5 feet, if available, prior to mining, b) segregate and save them according to land ownership, and c) respread them in two layers within the land boundaries of each landowner from which the soil was removed. However, upon landowners consent, respread across property lines was allowed. It was felt that by these elaborate soil investigations and procedures for soil removal and respreading, the inherent productivity of the land would be preserved. The final decision on whether the requirements of the law had been achieved and the mining company could be released from bond liability was still left to the discretion of the Commission.

Other important requirements mandated by the 1975 law related to the collection of premining environmental data, protection of rights of landowners, and bond liability. The operator was required to conduct archaeological, geological, and hydrological surveys as a part of the limited and extended mine plan. If any landowner's well was disrupted or diminished, the mine operator was required to replace or repair it at no cost to the landowner. A three stage bond release process was implemented whereby the operator could be released from 40% of bond upon completion of grading, an additional 30% after soil respreading, and the remaining 30% after all reclamation was completed. Required bond amounts were increased. Also, a new law, the Surface Owner Protection Act, was enacted to provide maximum constitutionally permissible protection to landowners from the adverse affects of mining.

The 1975 amendments to the reclamation law were not as drastic as those of the 1973 law, but they were important in clarifying the overall intent: to protect agricultural lands from degradation as a result of surface mining. Reclamation of agricultural lands did improve as a result of the 1975 law. Researchers found that plant growth and production generally increased as the total topsoil and subsoil respread thickness increased, at least to a depth of 28 inches (Power et al 1979). Environmental protection also increased as a result of the 1975 law. Mining companies were required to monitor surface and groundwater and to mitigate the adverse affects of mining on these resources.

Another revision was made to the law in 1977. This required mine operators to grade disturbed lands to the gentlest topography consistent with the adjacent landscape. Standards for evaluating the success of revegetation were also included in Commission rules at this time.

Regulation Of Mining Under SMCRA

On August 3, 1977 the 95th Congress enacted Public Law 95-87, entitled Surface Mining Control and Reclamation Act of 1977 (SMCRA). SMCRA continued in a developmental phase until March 13, 1979 when regulations implementing the Act were published in the Federal Register. Title V, Control of the Environmental Impacts of Surface Coal Mining, required that each state wishing to assume exclusive jurisdiction over regulation of surface coal mining and reclamation within its borders must submit a state program capable of carrying out the provisions of the federal act (SMCRA). In accordance with this provision, North Dakota's permanent regulatory program was approved by the Office of Surface Mining (OSM) on December 15, 1980.

Although North Dakota already had an effective regulatory program prior to enactment of SMCRA, several changes had to be made in order to comply with all the provisions of the federal act. The state had an interim program which became effective May 3, 1978. Some important changes at this time were that regulation of the use of explosives came under the Commission's jurisdiction, all runoff from disturbed areas had to be treated in sedimentation ponds, complete backfilling of final pits was required, and special rules regarding prime farmland were established.

For the approval of North Dakota's permanent regulatory program, it was necessary to make further amendments in its reclamation laws and rules. These amendments were made in 1979, and were designed to make the State program as effective as the federal program. The 1979 law designated areas prohibited from mining. It also required detailed statements of the probable and cumulative hydrologic impacts of proposed mining operations. Detailed quantitative premine vegetation data were required to be included with each permit application. Measurements of productivity, cover, diversity, and seasonality were required for reclaimed grasslands prior to request for bond release. No final bond release could be approved until a minimum of ten years after the last augmented seeding.

The changes included in the 1979 law probably had only minor effects on the overall quality of reclamation and environmental protection. But they did set forth means of assuring that extensive premining assessments would be made and also set performance standards to guide each phase of mining and reclamation.

Recent Regulatory Developments

There have been several recent modifications to the state program in the form of program amendments, law and rule changes, and policy memoranda. These have come about largely as a result of public comments, reclamation research, and input from the mining industry. Some of the important modifications relate to bonding, soil removal and respread, and methods to prove reclamation success.

In December of 1985, the Reclamation Division of the Public Service Commission issued Policy Memorandum No. 16 to Mine Operators. This policy established the "worst case" method of calculating reclamation costs for the purpose of bond liability. This method required calculation of the amount of money it would take for the Commission to have the permit area reclaimed if bond was forfeited when the maximum amount of reclamation work was outstanding during the permit term. This method replaced the per acre cost assessment method in which different levels of bond were required per acre, depending on the level of disturbance. The per acre method often resulted in overbonding because it required a bond amount for each acre within the permit area irrespective of whether it would be disturbed during the five year permit term or not. The new bonding method provided a reasonable estimate of reclamation costs at the "worst case" during the permit term. It continued to ensure adequate money for reclamation in the event of bond forfeiture, without unnecessarily requiring bond for each permitted acre, and consequently saved money for the mining industry. Further changes were made to rules regarding bond requirements in 1988. These changes allow self bonding by a permit applicant in some instances.

A rule change was adopted in January of 1987 that affected the amount of subsoil that had to be saved and respread. This rule change was largely based on research conducted by North Dakota's Land Reclamation Research Center and the USDA/ARS Northern Great Plains Research Center in Mandan. This research concluded that the amount of subsoil needed for respread should be based on underlying spoil quality. Where mining companies were previously required to remove all soil identified by the soil survey, they could now remove a lesser amount of subsoil if the overburden was of satisfactory quality. Again, the state program was made more efficient; the quality of reclamation was maintained, but at a lower cost.

In 1989, after years of formulation, complete guidelines for the collection and evaluation of revegetation data for final bond release were completed by the Reclamation Division. Previously, the only approved method for evaluating revegetation success was by comparing unmined reference areas to reclaimed areas to determine if the reclaimed lands had achieved a level of vegetative productivity equal to or greater than that which existed prior to mining. This required that the mining companies manage and monitor a duplicate undisturbed tract of land in the same manner as the reclaimed tract. By using the new revegetation guidelines, they now can establish success standards for revegetation by a number of other methods using SCS data that relate productivity to soil series. These revegetation guidelines were the result of a cooperative effort between the reclamation division and the mining industry and were the first of their kind to be approved by OSM. This document will undoubtedly be used to develop similar revegetation guidelines for other states.

Summary and Conclusion

This paper provides a brief discussion of the history and importance of lignite mining in North Dakota, and the negative environmental impacts that were associated with mining prior to the reclamation law. It also outlines the development of the State's regulatory program that established the requirements for the reclamation of mined lands. This program began very simply, merely requiring the mine operator to obtain a permit, to grade spoil peaks, and to seed them. Within six years, it developed into a complete regulatory program requiring that the land be restored to its premining level of usefulness, or better, after mining. The further developments that occurred in the program following enactment of SMCRA are also discussed. Presently, the State Program is as effective, and in some cases more stringent, than the federal program.

The success of North Dakota's mining and reclamation regulatory program is evident by the fine reclamation that has been achieved in the state. The state's reclaimed mined lands include highly productive farmlands, rangelands, well maintained industrial sites, and fish and wildlife areas including reconstructed wetlands that have been cited by the federal Office of Surface Mining for their excellence. In fact, mined lands in North Dakota have been reclaimed to as diverse uses as a golf course and an airport.

There are several reasons for this success. First, the commitment of the people of the state against leaving wastelands behind after mining. Secondly, the wise administration of the state's program: taking gradual steps and working cooperatively with other state and federal agencies, the research community, and the mining industry. Thirdly, the research community in the state provided much needed research as a basis for improving reclamation technology. Finally, the efforts and cooperation of the mining industry in its willingness to go the extra mile to reclaim the land appropriately and to prevent offsite impacts of mining to the highest degree possible.

What about the future of mining and reclamation and its regulation in North Dakota? Only time will tell. But it appears that it will continue to be as dynamic as in the past, balancing the economic needs of the state with the need to protect the environment.

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ECONOMIC CONSIDERATIONS AFFECTING WILDLIFE HABITAT RECLAMATION IN FLORIDA'S PHOSPHATE MINING INDUSTRY[1]

by

TIMOTHY P. KING[2] and WAYNE R. MARION[3]

Abstract. Phosphate mining in Florida is a major industry affecting thousands of acres of fish and wildife habitat each year. Reclamation has traditionally favored the creation of simple grassland or forest plantation systems that are relatively inexpensive to create and in tune with the principal land uses in each of two distinct mining districts. However, international market conditions have set the industry on an economic decline that will likely result in increased emphasis on reclamation cost savings and recreational land uses. It is expected that this will positively influence habitat reclamation in the industry. This paper describes the present economics and costs of reclamation in the Florida phosphate industry and presents a scenario of how habitat-specific reclamation might be improved in response to the changing economic setting.

Additional Key Words: economics, wildlife, habitat, reclamation.

Introduction

Florida's phosphate mining industry has a major influence on habitat changes taking place over extensive areas of land in its central and north Florida mining districts. The Florida mining industry accounts for about 76% of U.S. phosphate rock production and this has accounted in recent years for about 15% to 20% of total world production (Stowasser 1986). Florida reserves are mined from open pits at a rate that ranged from 5,000 to 6,000 acres per year during the mid-1970's to mid-1980's (Fla. Dept. of Natural Resources 1989). However, a recent economic downturn and ensuing changes in the international fertilizer market reduced U.S. operations in 1986 to 63% of capacity. The result was a period of mine closures, sales, mergers, and product shifts, some of which continue to this day.

While the expectation is for the industry to again peak in 1990, the depletion of the high grade reserves most in demand on the new international market should bring about a steady drop in Florida production to about 30% of the 1990 peak by the year 2010 (U.S. Bureau of Mines 1989). This decline in production will likely stimulate industry promotion of environmental and land use values of reclaimed land, while adding additional incentives to reduce reclamation costs. These emerging economic trends could have a positive effect on habitat reclamation in the state by encouraging more low-cost, higher-relief landforms and hunting and fishing land use options that are attractive to the public for recreational purposes.

Phosphate Mine Reclamation

Recreational Potential

The recreational potential of phosphate mined lands in Florida has been well demonstrated and publicized. Based on our own survey, there are presently 12 state, county, and municipal parks and reserves on mined lands totaling 11,295 acres. Most of the smaller parks are used for fishing, picnicking and team sports, while the larger parks and state reserves include hunting, hiking, camping and nature study in their land use plans. Of the 11 companies presently in operation, 6 have private sportsmen's clubs controlling recreational access which is generally limited to mine company employees or their guests. Public hunting or fishing areas have, however, been operated in both mining districts. In each instance, public demand for hunting or fishing opportunities far exceed their availability.

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While phosphate companies have shown their ability to create attractive recreational lands and would likely want to expand public use and appreciation of their holdings as reserves are depleted, it becomes a question of how to meet the recreational land use demand under the regulatory and economic constraints under which the reclamation programs must operate. In other words, is the demand compatible with environmental regulations, and can it be achieved at a cost and potential return on investment sufficient to be an economically viable option?

Reclamation Regulations

Of the various administrative rules covering reclamation practices of the Florida phosphate mining industry, the two that most explicitly affect the extent of post-reclamation habitats are the requirements that wetlands be replaced on an acre-for-acre basis and that upland forest be established over at least 10 percent of the total upland area. The state's pre-mining regulatory review process also requires either preservation or full replacement of critical habitats - especially river or stream channels, floodplains, and unique, xeric (dry and sandy) scrublands.

Protection of Florida's natural lakes and streams also has brought about an increased regulatory demand for whole watershed planning aimed at minimizing mining-induced changes in the quality or quantity of site runoff or discharge. Implicit in these regulatory objectives is an emphasis on replacement of pre-mining watershed boundaries and topographies. However, except for those instances where a site's design might affect regulated water quantity or quality goals, there are no requirements on how land uses must be arranged on the landscape. However, the state does encourage creation of greenbelts and wildlife corridors, and the incorporation of lake, wetland and stream projects into the comprehensive design for a whole watershed.

One other important reclamation regulation from a fish and wildlife standpoint is the "wildlife areas" rule. This rule would allow a landowner to designate specific areas of a mine as wildlife habitat, and include a plan for the reclamation and management of sites so designated in the usual state reclamation application. For such areas, slopes, revegetation and erosion control requirements may be waived or modified on a case-by-case basis where such changes will benefit the overall plan for production of wildlife. The intent of the rule is to allow a mine owner the option of retaining environmentally compatible, but obviously mining-induced landforms that might inherently offer greater habitat or recreational values than those resulting from other regulations aimed at replacing pre-mining landforms.

Reclamation Costs

Earthmoving is the most energy demanding and most costly aspect of reclamation. Based upon formulas used for the reimbursement of reclamation costs in the state-funded, abandoned lands program, on-site earthmoving can be 7 times more costly than revegetation. Where fill also must be pumped in from elsewhere in the mine to replace mining voids, this can add substantially to the total reclamation costs. However, backfilling is usually accounted for as a production cost since it may be considered as part of the mine waste disposal process.

In Florida, sand and clay tailings from ore beneficiation are suitable materials for use in backfilling. These materials are pumped into a reclamation site at a cost determined by the number of kilowatt-hours needed per ton-mile pumped. As a scenario based on figures from one central Florida company, backfilling with sand tailings can average almost $12,000/acre. This is based on a mining void that typically requires 15 acre-feet of material to reach pre-mining grade, an acre-foot of sand tailings that weighs 2,393 tons, 2.2 kilowatt-hours/ton-mile that is required for pumping, the cost of a kilowatt-hour that can run up to $0.05, and a reclamation site that averages about 3 miles from the mine plant. From this, it can be seen that a requirement that pre-mining topography be restored in remote areas of a mine can be a costly reclamation objective.

While revegetation costs cannot match earthmoving costs, they can represent a considerable per acre expenditure depending upon the complexity of the vegetation type being targeted. Obviously, it will cost more to reclaim a multi-layered forest than a simple grassland or timber plantation, and each technique used to establish the stand will add to the total reclamation cost. Generally, the greater the regulatory demand for a particular community type and the more extreme the soil moisture conditions under which it must be established, the more subsidy required to create the stand and the more costly the revegetation program.

Grassing is the most widely used revegetation practice in central Florida, with costs reported at between $75 and $150 per acre (from an informal survey of several leading companies). In north Florida, where pasture is not a common reclamation goal, grassing costs can run considerably higher. Establishment of a stabilizing ground cover may be required in any revegetation program and thus, grassing may be an additive cost even in projects aimed at self-managing communities.

Establishment of native herbaceous species also is required of most permitted habitat creation efforts, although the standards for success are generally negotiated on a case-by-case basis. The methods used are either direct planting, topsoiling, or sometimes both. Transplanting of herbaceous wetland species acquired from off-site habitats is the typical method of obtaining plant material for wetland reclamation. Costs are reported to range from approximately $100/acre to $750/acre. Transplanting costs for upland species would fall within the same broad range, although too few such projects have been completed to provide an industry-wide estimate. Mulching with topsoil is regarded as a more effective method of introducing vegetation, but it is more expensive. Reported costs range from $800/acre to $2000/acre.

For successful forest establishment, 200 trees/acre are required for uplands while 400 trees/acre are required for wetland forests. Twice as many trees are usually planted to assure adequate survival with reported costs ranging from $500/acre to more than $1600/acre. Tree planting costs in the forestry-dominated northern district tend to be significantly less. However, in both mining districts, higher mortalities on harsh wetland or xeric sites often can require costly replanting.

A final element of reclamation costing is the program design work. Here, the cost does not depend upon the site's final layout. Yet a site design can have considerable influence over the wildlife habitat values achieved in any particular program. Given any land use acreage goal, there may be any number of site design options, each having some distinct value to a particular fish or wildlife assemblage. Design considerations for the "cost-free" enhancement of reclaimed habitat values have been developed for the industry (King et al. 1985), and, based upon comparison of earlier plans with more recent plans submitted to the state for approval, incorporation of these design enhancements is occurring (Marion and King 1988). Wildlife travel corridors, valuable community edge combinations, and isolation of proposed habitats from areas with high land use potential can help increase fish and wildlife values while minimizing conflicts with developing, post-reclamation land uses.

Incentives for Habitat Reclamation

Beyond incentives offered by the state's regulatory processes, the extent and quality of habitat reclamation in Florida depends upon its economic justification to the company or private landowner holding the mined lands. Either the necessary habitat infrastructure must be a non-interfering, low-cost part of a viable economic sub-system, or it must be capable of generating its own financial return.

In central Florida, native rangeland and forest habitats are declining in the post-reclamation landscape (Table 1) because the potential return on investment of reclaiming to these vegetation types has not met the demonstrated costs. Cattle ranching is a leading land-use in the region; and, in reclaimed by habitat/land use type in Florida the pre-mining situation, native range provides grazing land that needs little management. On

Table 1. Reclamation in Florida's phosphate mines by habitat/land use type, 1975-1989.

Habitat/Land Use Type	Acreage Reclaimed
Forested Uplands	5,232
Non-Forested Uplands	19,739
Herbaceous Wetlands	2,025
Forested Wetlands	2,510
Lakes	4,188

Source: Florida Department of Natural Resources (1989 pers. comm.)

the other hand, reclaiming to a similar rangeland vegetation type requires either topsoiling or intensive herbaceous plantings (or both), and can be considerably more costly than reclaiming to pasture. It has yet to be shown whether any long-term savings in land management expenses for reclaimed rangeland can fully offset the increased reclamation costs.

Timber sales might provide an added incentive to reclaim to forest or multiple-use (e.g. cattle/timber/game), although volume yield tables for typical reclaimed sites in the central district have not yet been developed. There have, however, been numerous tree plots established over the years for demonstration or research purposes. These plots demonstrate the ability to establish stands of commercial pines over most reclaimed sites and the potential of establishing hardwood stands on clay or sand/clay mix tailings ponds that cover a majority of the post-mining landscape. While hardwood timber is not currently grown in sufficient volume to be a viable commercial product in central Florida, there are many local buyers that presently rely on shipments of hardwoods from the north. If yields from these unique but extensive clay sites should prove sufficient to offset the cost of transporting needed timber into the region, then the incentive to reclaim to forest land might be sufficient to overcome the decline in forested habitats presently occurring in the area.

But, management cost savings and potential timber harvests are not the only incentives that can be applied to rangeland and forest reclamation. Leasing land for hunting purposes is a growing practice in the south and southeastern U.S., with over 50% of the privately owned land in Florida leased for hunting (Wiggers and Rootes 1987). Based on a survey of hunting lease arrangements in Florida (Marion and Gates 1988), average returns for hunting leases were $2.29 in 1984, but average returns of up to $5.00/acre/year are not uncommon. The highest lease returns in the state occur near the central mining district (Table 2). A diverse rangeland or forest community can offer more hunting potential than a pasture, and hunting lease arrangements can be compatible with grazing and timbering schedules. Given the growing

Table 2. Average prices per acre for leasing access for hunting in Florida, 1984.

District	Average lease prices/acre
Florida Panhandle	$1.69
North Florida	$1.32
Central Florida	$2.73
South-Central Florida	$2.34
South-West Florida	$1.74

Source: Marion and Gates (1988).

demand for outdoor recreational opportunities in the state, and the potentially increasing incentive within the industry to promote a wider range of land use options, it may be that consideration of hunting lease returns could justify further development of cost-effective rangeland, forest or multiple-use options for reclaimed uplands.

Reclaimed lakes and wetlands, on the other hand, have proven to be attractive, sought-after hunting and fishing areas in both regions of the state. The extensive areas of open water that typify active clay ponds and unfilled mine cuts, maintain large populations of waterfowl and sportfish that can support some of the best hunting and fishing in the state. They also can support a level of recreational use that is attracting local entrepreneurs. At one recently closed mine, the corporate landowner is leasing 1400 acres of former mine pits for bass fishing at a rate comparable to local grazing leases, and two- to three-times greater than the average hunting lease return (Marion 1989). The lessee, in turn, is offering access to the site to the fishing public for a daily fee. At another 540-acre abandoned mine pit area, a sportsmen club has purchased the site from the corporate landowner and is having it reclaimed to private hunting and fishing through the state's abandoned lands program. These are but the initial examples of what may be a growing trend toward fish and wildlife habitat reclamation for recreational use in Florida's changing phosphate mining economy.

Outlook for Habitat Reclamation

Habitat reclamation in Florida has shown improved sophistication in planning accuracy, implementation technique and impact mitigation potential over the past decade (Marion and King 1988). Nevertheless, substantial habitat and land use changes have been an inherent part of the traditional mine economic setting. Whether a higher future proportion of land is devoted to fish and wildlife use will depend on incentives that emerge in a changing economic setting. These incentives would need to either increase the regulatory requirement for habitat acreage or value, lower habitat reclamation costs, or provide a higher return on investment for habitat objectives.

The outlook for mining and reclamation permits requiring greater habitat reclamation in the future is not overly promising. Critical habitats are either being preserved or restored on an acre-for-acre basis under the current regulatory structure. While there is consideration being given to requiring more than even compensation for some wetland mitigation projects, this is meeting considerable opposition and would likely conflict with the existing regulatory emphasis on restoring pre-mining drainage patterns and rates.

The outlook for lowering habitat reclamation costs seems more promising. Experience in habitat reclamation has grown in the industry since the first wetland habitat projects were undertaken in the late 1970's. With this experience has come improved program design, better planting success, and a more cost-effective set of reclamation practices.

Taking further advantage of habitat values that can be gained from an effectively planned program design also can occur. Computational algorithms that assess the habitat value inherent in a site's landscape design are beginning to emerge in the literature and soon could be employed in the industry to help optimize the planning of individual programs for wildlife.

Beyond the cost savings from added experience and expertise in optimizing habitat reclamation programs, there could be a cost saving and financial return incentive from any trend toward increased recreational land use. Although hunting and fishing leases are not, in themselves, a high return land use, they are compatible with forestry or cattle grazing under multiple use scenarios. The added return from hunting and fishing leases could help justify the added expenses of reclaiming to the forest and rangeland vegetation types most in decline in the state due to mining. In addition, most of the recreational use of phosphate mined lands is water-oriented, or located on the more aesthetically pleasing lands surrounding waterbodies. If more of this type of opportunity is desired, then this will undoubtedly translate into a reclamation objective calling for more waterbodies and wetlands. The potential savings from not having to backfill mined lands to pre-mining grades could be considerable.

A possible scenario for the future might be for the industry to take greater advantage of the state's "wildlife areas" rule to create large tracts of relatively inexpensive, publicly-owned, recreational lands. Such tracts would need to be situated in areas where they complement a region's natural drainage patterns, and be of a size sufficient to justify their acquisition and management as public lands. Surrounding lands could, in turn, be reclaimed as a habitat priority, land use buffer allowing private, recreation-oriented enterprises and supplying connections to other significant habitats in the region (Fig. 1). Whether the industry undertakes the scale and degree of land planning necessary to justify and implement this scenario will depend, in the end, on social demand and economics.

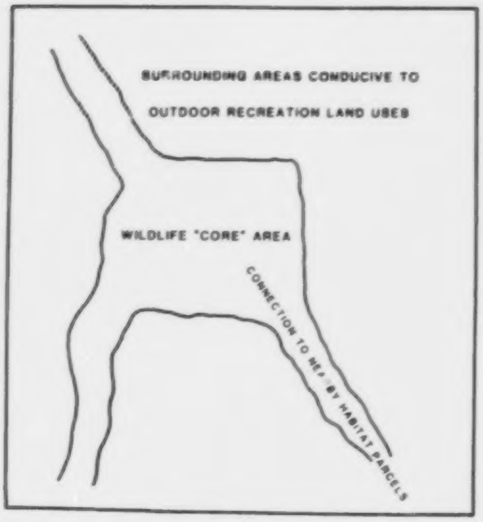
SURROUNDING AREAS CONDUCIVE TO
OUTDOOR RECREATION LAND USES
WILDLIFE "CORE" AREA
CONNECTION TO NEARBY HABITAT PARCELS

Fig. 1. An aerial view of an area showing beneficial wildlife habitat features.

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REHABILITATION OF THE RUM JUNGLE MINE SITE[1]

by

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Abstract. A rehabilitation program was carried out at the abandoned uranium/copper Rum Jungle mine site in the Northern Territory, Australia, between 1982 and 1986. The results of post-rehabilitation monitoring show that the surface water quality criteria have been met. There is some decrease in water quality of the flooded open cuts during the dry seasons but the quality improves with annual wet season flows. The covers on the waste rock dumps continue to limit the infiltration of water and the oxidation of pyrite.

ADDITIONAL KEY WORDS: Uranium; Copper; Acid mine drainage; Reclamation; Surface mining.

Introduction

The long term control of acid drainage and the release of heavy metals from abandoned mine sites can be a major environmental problem long after mine operations cease. Control of these pollutants is essential if mining is to be a temporary land use. It is important to establish the effectiveness of different rehabilitation programs so that the international community can benefit from the lessons learnt at different sites. This paper describes the rehabilitation of the Rum Jungle mine site and the results of monitoring in the two years since the completion of the rehabilitation works.

Rum Jungle Mine Site

Open cut mining to extract uranium/copper ore was carried out at Rum Jungle in the Northern Territory, Australia, between 1954 and 1964. Figure 1 shows a map of the location. The East Branch of the Finniss river flows through the site. Three main ore bodies were mined using open cut techniques. When the site was abandoned in 1971 there were three water-filled open cuts, four waste rock heaps (dumps) containing pyritic material, a tailings disposal area and a pile of low grade ore where an attempt had been made to extract copper by heap leaching, Figure 2.

The largest of the open cuts was White's which was completed in 1958 at a depth of just over 100 m. The waste rock from this open cut was formed into a dump the top of which was

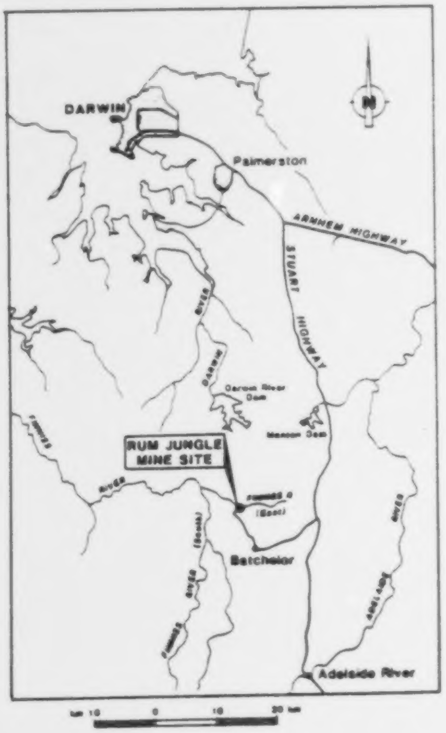

Figure 1. Location of Rum Jungle Mine Site

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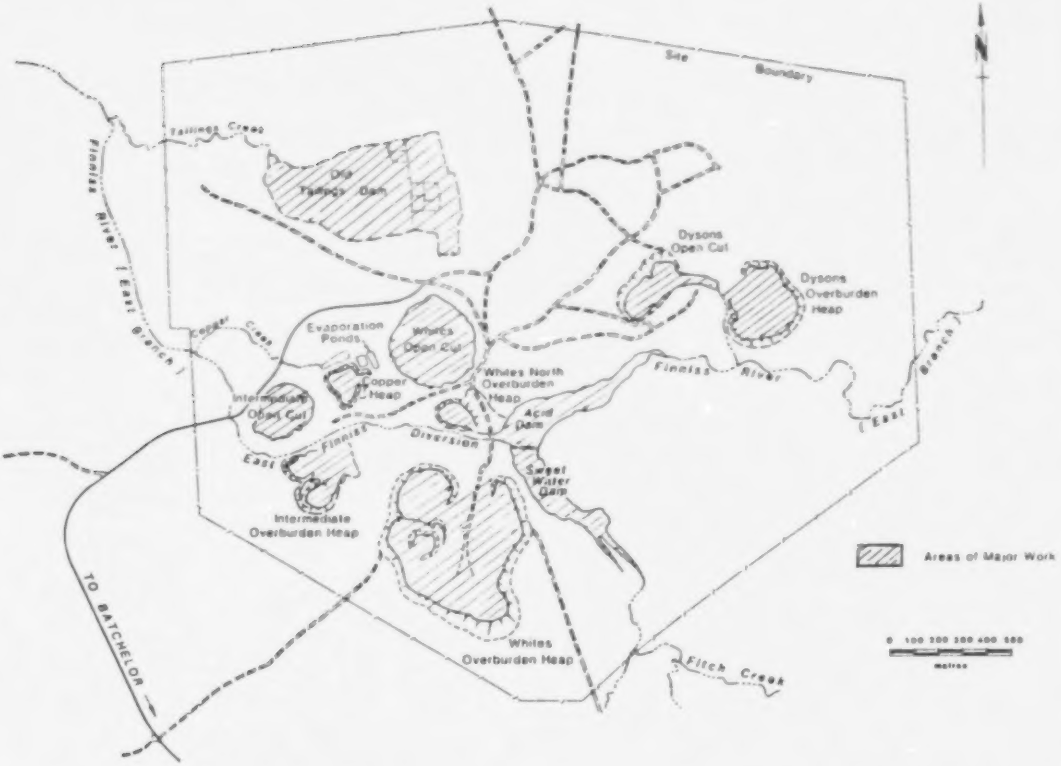
Site Boundary
N
Tailings Creek
Old Tailings Dam
Finniss River (East Branch)
Copper Creek
Evaporation Ponds
Whites Open Cut
Intermediate Open Cut
Copper Heap
Whites North Overburden Heap
Acid Dam
Dysons Open Cut
Dysons Overburden Heap
Finniss River
(East Branch)
East Finniss Diversion
Sweet Water Dam
Intermediate Overburden Heap
Whites Overburden Heap
TO BATCHELOR
Fitch Creek
Areas of Major Work
0 100 200 300 400 500
metres

Figure 2. Site plan prior to rehabilitation.

some 13-18 m above the original ground surface and was generally smooth and well graded. The top surface sloped gently down towards the centre of the dump where a main drainage channel collected run-off. The sides were steep (about 30°) and made up about 25 percent of the 26.4 ha area of the whole dump.

White's overburden dump contains about seven million tonnes of material consisting of carbonaceous shales and graphitic schists with an average sulphur content of 3 per cent, mainly in the form of pyrite. Some dolomite is interspersed through the dump.

Dyson's ore body was mined between 1957 and 1958. The overburden dump was similar in shape and composition to White's but smaller with a content of about two million tonnes and an area of 9 ha.

In 1963, the Intermediate ore body, which was only about 500 m west of White's ore body, was also extracted by an open cut operation. This ore body was mined for its copper content not its uranium content. The waste rock dump had an area of about 7 ha and contained about two million tonnes of material with a similar composition to that in White's dump. The oxide and low grade sulphide ore from the ore body were placed in a heap leach pile where an attempt was made to extract the copper by heap-leaching techniques.

Significant pollution of ground and surface waters with acid and heavy metals was apparent when mining operations ceased. An extensive survey in 1973-74 [Davy, 1975] showed that the major sources of pollution were the waste rock dumps and the heap leach pile, copper being the main heavy metal pollutant.

It should be emphasised that the environmental impact of the post-operational phase of the Rum Jungle mine came more from the association between its ore and pyritic material than from uranium in the ore.

Rehabilitation Objectives and Strategy

The Rum Jungle mine site was rehabilitated between 1983 and 1986 by the NT Department of Mines and Energy (NTDME) using money provided by the Commonwealth Government. The total cost was $(Aust)18.6 million of which $2.8 million was spent rehabilitating the three waste rock dumps (NTDME 1986).

The objectives stated in the 1982 agreement between the Northern Territory and the Commonwealth Governments were: a major reduction in pollution in water courses feeding the East Branch of the Finniss River and in particular the reduction of the annual average releases of copper, zinc and manganese into the river by 70 per cent, 70 per cent and 56 per cent respectively; a reduction in public health hazards and in radiation levels at the site; a reduction of pollution in the water contained in White's and Intermediate open cuts; and aesthetic improvement including revegetation.

The strategy adopted for the waste rock dumps was based on the premise that a reduction in infiltration of rain water into the dump material would reduce the pollution load to groundwater and from there to the East Branch. The strategy was implemented by covering the dumps with a three layer system: the first a compacted clay layer to act as a moisture barrier; the second a layer of sandy loam as a moisture retention zone to support vegetation and prevent the clay layer drying out; while the uppermost layer was gravelly sand to provide erosion protection and act as a pore breaking zone to restrict moisture loss by evaporation in the dry season. Before the layers were put in place the dumps were reshaped so that the tops had a maximum slope of 5° and the sides a maximum slope of 1 in 3. On the top of the dumps the layers had minimum thicknesses of 225 mm, 250 mm and 150 mm while on the sides they had minimum thicknesses of 300 mm, 300 mm and 150 mm. On the sides crushed rock replaced gravelly sand as the erosion barrier.

Engineered runoff channels and erosion control banks were constructed on the tops and sides of the dumps. Vegetation was established to stabilise the dump surface against the long-term effects of erosion.

The tailings from the tailings area together with any contaminated subsoil were removed and dumped into Dyson's open cut. A rock blanket was constructed on a geotextile fabric over the placed tailings to provide a drainage path for pore water. The material from the heap leach pile was dumped on top of the rock blanket. This strategy meant that the tailings were well contained and the heap leach material was above the water table. The filled open cut was covered with the same three layer system used for the waste rock dumps.

A water treatment plant was built to treat the polluted water in both White's and Intermediate open cuts using lime neutralisation. The difference in density between the water in White's open cut and the treated water meant that it was feasible to return the treated water to form a stratified layer above the polluted water in the open cut. White's open cut was treated to a depth of 22 m.

The density of the polluted water in the Intermediate open cut was less than that in White's and it was not possible to use stratification to separate the treated water from the polluted water. The polluted water in Intermediate was treated in situ by direct addition of hydrated lime, with the subsequent removal of the precipitated sludge from the bottom of the open cut.

After the open cuts had been treated the East Branch of the Finniss River was redirected to its original channel through both open cuts. A set of weirs was constructed to limit flow through the open cuts by directing low flow and a large fraction of flood flow down the diversion channel. This annual flushing of the open cuts is designed to prevent the build-up of acidity and metals.

In addition to the main problem areas at the site, revegetation and earthworks were carried out on the river banks, stockpile areas, and borrow pits.

Surface Water

The main gauging station for evaluating the surface water quality from the mine is GS8150097 which is downstream of all mine pollution input. The location of the station is shown in Figure 3. Water samples collected at GS8150097 consisted of twelve, two-hourly samples, each being a composite of three samples taken at 40 minute intervals using an automatic sampler. A daily composite was prepared according to the average discharge for the twelve two hour periods. Water samples were analysed for pH, specific conductance, copper, manganese, zinc and sulphate concentrations. Separate samples were collected for radium analysis.

Daily rainfall was measured using two pluviometers at the locations shown in Figure 3.

As stated above, one objective of rehabilitation was to reduce the annual loads of copper, manganese and zinc in the East Branch. The pollutant load in the East Branch is known to be very dependent on the total annual

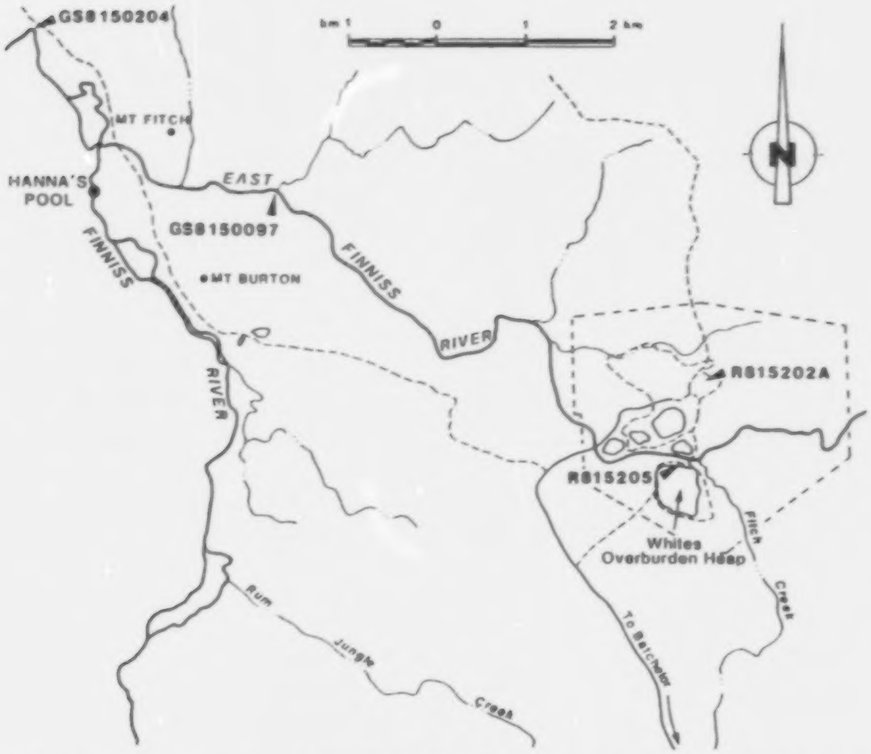

Figure 3. Locations of gauging station GS8150097 and pluviometers, R815202A and R815205.

discharge. Hence the water quality objective has been interpreted to mean that the reduction refers to years of similar river flow.

Figure 4 compares the load of copper in the East Branch during and since rehabilitation to the loads measured before rehabilitation between 1971 and 1973. Since the completion of rehabilitation in 1986 all of the wet seasons have had a very low rainfall and hence a low river discharge. Nevertheless the copper load, and the load of other pollutants, is much less than that indicated by the pre-rehabilitation relationship. In the 1987-88 wet season the pollutant loads were copper 3.2 t, manganese 5.4 t, zinc 2.0 t and sulphate 1230 t. These loads indicate reductions of 90, 90 and 80 per cent for copper, manganese and zinc respectively from the pre-rehabilitation annual load vs discharge relationship.

The maximum daily concentrations for copper, manganese, zinc and sulphate in 1987-88 were 4.4, 4.0, 6.9, and 950 mg/L. All these maxima occurred at the start of the wet season at very low flows when most of the flow comes through the diversion channel. The high level of pollutants at this time is thought to arise from the dissolving of residual salts in the water courses and the rising of the polluted water table; a first flush effect.

Surface water qualities have been measured at various locations around the site to estimate the contribution of different sources to the pollution load. In the 1987-88 wet season the open cuts contributed 65, 58, 3 and 48 per cent of the copper, manganese, zinc and sulphate leaving the site.

An above-average wet season is needed to fully test the integrity of the engineering works and the pollutant load under high flow conditions.

Open Cuts

Water quality profiles have been measured throughout the wet season. The results confirm that the open cuts, particularly White's, are major contributors to copper and manganese pollution in the East Branch of the Finniss River.

The water quality in the top 29 m of White's open cut improves during the wet season as a result of the flow of better quality water across the open cut. The top 29 m lost about 9 t of copper and 15 t of manganese. The difference in the pollutant concentrations between the relatively unpolluted water flowing into the open cut and the more polluted water flowing out from the open cut only accounted for about 2 t of the copper and 2.5 t of the manganese. It appears

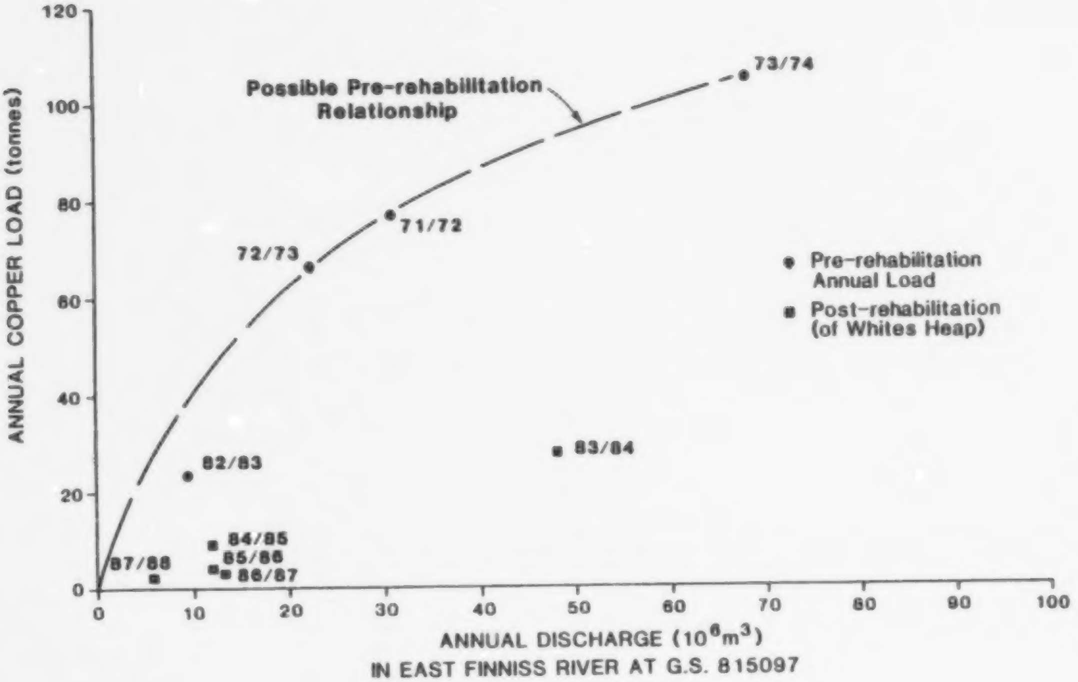

Figure 4. Annual copper loads in East Branch versus annual discharge for various years.

that the high pH water entering the open cut causes precipitation of dissolved heavy metals that sink towards the bottom where they redissolve in the lower pH bottom water.

The water in the top 30 m of Intermediate open cut has been largely replaced by overflow water from White's open cut.

The level of pollutants increases in both open cuts during the dry season probably due to mixing caused by thermal effects and wind action and due to polluted groundwater entering the open cuts.

Overburden Dumps

The main aim of covering the dumps was to reduce ingress of water and thereby reduce the release of pollutants. Sets of lysimeters were installed in the reshaped White's and Intermediate dumps before emplacement of the clay layer. The amount of water collected by the lysimeters in White's dump in each of the three wet seasons between 1985 and 1989 is equivalent to less than 2.5 per cent of the incident rain. That collected in lysimeters in Intermediate dump corresponds to less than 5 per cent of the incident rain. These infiltrations are much less than the 50 per cent of the incident rain which percolated through the dumps before rehabilitation and indicates that the compacted clay cover achieved the desired reduction to 5 per cent or less of incident rain.

Probe holes have been drilled down to the original ground surface in White's and Intermediate dumps to provide access for measuring temperature, gas composition and water content.

Heat Production

Before rehabilitation, the temperatures at some locations within the dumps exceeded 50°C, Figure 5. The elevated temperatures were caused by the release of heat in regions where pyritic oxidation was occurring. A one-dimensional heat transfer model has been used to derive the distribution of heat production in the dumps from vertical temperature profiles measured before and after rehabilitation (Harries and Ritchie 1980, 1987). The rate of oxidation of pyrite can be obtained directly from the heat source distribution using the heat of reaction.

Before rehabilitation, heat production was occurring in White's dump at depth in many locations. After rehabilitation, the heat production was either very low or zero at all measuring locations, Figure 5. Comparison of heat production distributions before and after

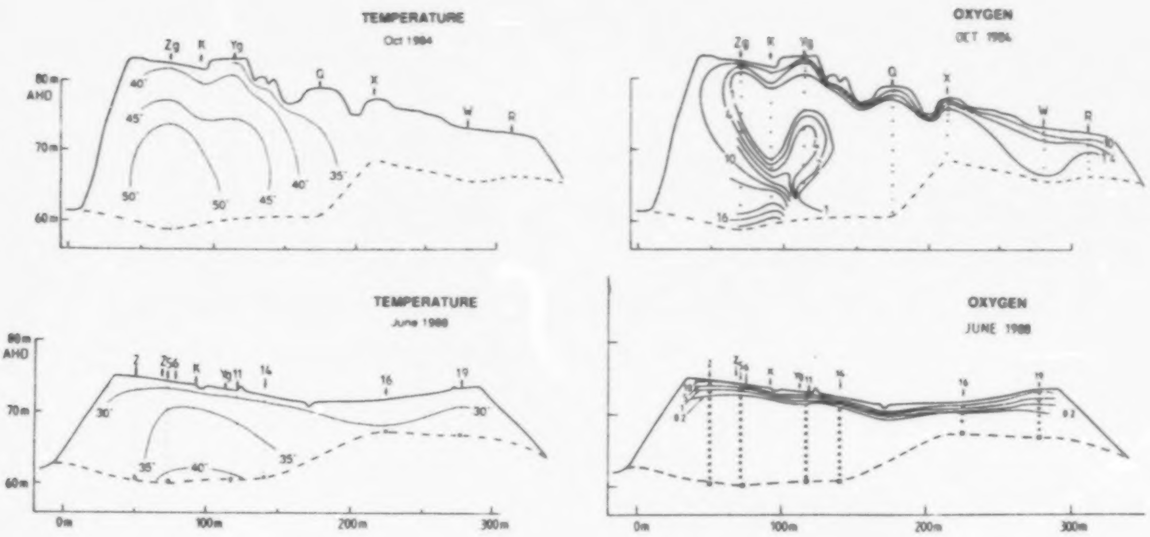

Figure 5. Temperature and oxygen distributions in Intermediate dump before (Oct 1984) and after (June 1988) rehabilitation. Temperature contours are marked in °C and oxygen contours in percent oxygen (by volume)

rehabilitation shows that the oxidation occurring before rehabilitation was effectively stopped by rehabilitation.

Pore Gas Composition

The supply of oxygen was the main process limiting the rate of oxidation in the Rum Jungle waste rock dumps before rehabilitation. Measurements of oxygen concentration in the pore gas showed that oxygen was transported to the oxidation sites by a combination of diffusion, thermal convection, and advection driven by variations in atmospheric pressure (Harries and Ritchie 1985).

Each of the oxygen transport processes leads to a characteristic oxygen concentration profile. Thermal convection causes the oxygen concentration to be higher near the base of the dump. Diffusion causes the oxygen concentration to decrease monotonically with depth. Advection driven by variations in atmospheric pressure leads to short-term changes in oxygen concentration over timescales of less than a day.

At tropical locations like Rum Jungle, the dominant atmospheric pressure variations are atmospheric tides which have two maxima and two minima a day. Increasing pressure causes air to flow into the pore space and, because the incoming air has a higher oxygen content than air already in the dump, the oxygen concentration measured at a given point increases. This can cause diurnal variations in the oxygen concentration at a given point in the dump with two maxima and minima a day.

The emplacement of the compacted clay covers greatly reduced the level of oxygen in most regions of the dumps. Figure 5 shows the temperatures and oxygen concentrations in Intermediate dump before and after rehabilitation. Before rehabilitation there was a tongue of oxygenated air at depth in both dumps which indicated that thermal convection was transporting oxygen in from the sides of the dumps and up through the hot regions. Since rehabilitation, the oxygen concentrations at depth have been low. The clay cover effectively stopped oxygen transport by thermal convection.

The oxygen concentrations were found to be low in the dry season and there was no diurnal variation. In the wet seasons oxygen concentrations were still generally low but diurnal variations reappeared near the surface early in the wet season. This is taken to indicate that there were some cracks in the clay layer in the dry season with the cracks providing paths over the whole dump surface for advection of air by atmospheric pressure variation. The reappearance of the diurnal variations in the wet season indicates that most of the cracks closed as the moisture content of the clay increased but the clay near the monitoring holes did not seal as well as that further away.

Groundwater

Intensive groundwater monitoring at the site started in mid 1983. Since that time the number of boreholes has increased to a total of 70 boreholes, with about 35 in the vicinity of White's dump. This overburden dump was the major source of pollution before rehabilitation and groundwater was the principal pathway for the transport of the pollutants to the East Branch.

The monitoring data show that the concentration of pollutants in 1988 in the groundwater close to the dumps was substantially the same as before rehabilitation. The reduced infiltration of rainwater into the dump indicates that there is a reduction in the flow of groundwater from the dump and hence a reduction in the pollutant load. It is calculated that there is a large store of pollutants held in the pore space and that it could take 10 to 20 years for this store to be depleted (Gibson and Pantelis 1988).

Vegetation Establishment

Revegetation at the site was undertaken using introduced tropical pasture species following the completion of the earthworks and at the commencement of the wet season.

The long term stability of the rehabilitated site and the integrity of the earthworks depends on maintaining a sound vegetation cover to minimise erosion of the surfaces.

Monitoring of the vegetation since the 1984 has indicated marked changes in species composition of the revegetated surfaces. Initially the pasture grasses dominated, but with each successive wet season there has been an increase in both introduced legume species and naturalised/native colonisers from the surrounding land. Most of the introduced species achieve two to three seed sets each wet season ensuring an ever increasing seed bank in the soil.

Vegetation cover on the rock mulched batters commenced slowly but after five wet seasons nearly 50 per cent of the larger batters are vegetated. This is expected to continue as the surficial erosion washes soil between rocks and creates a suitable seed bed on the batters.

Some of the revegetated surfaces have been subjected to fire during the dry season but recovery of the pasture in the wet season has been very satisfactory. Colonising of the surfaces with native tree and shrub species has not been vigorous, with the exception of *Acacia* species and fire has slowed their expansion.

After five years the surfaces appear quite stable and soil erosion has not been a significant problem. Some stability problems have been experienced with rip-rap drains, usually where design criteria were not strictly adhered to during construction

Conclusions

Monitoring at Rum Jungle has shown that rehabilitation of the site has been successful.

Monitoring is an important part of rehabilitation because it tests the success of the work in meeting design criteria. Monitoring for the two years following completion of the earthworks was costed as part of the Rum Jungle project. The results from monitoring will allow the cost-effectiveness of the Rum Jungle rehabilitation project to be assessed and used as a benchmark for rehabilitating other mine sites where there are pyritic wastes.

The data obtained to date show the importance of continuing to monitor the site for an extended period. It is planned to continue to monitor surface water, groundwater and oxidation in the dumps for the next five years (Verhoeven 1988). This extended monitoring program will involve less frequent measurements than between 1986 and 1988 but should be sufficient to identify trends and determine the long-term effectiveness of the rehabilitation works.

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Sodic and Saline Materials

Session Chairman: R.L. Johnson

SUBSOIL THICKNESS EFFECTS ON CROP YIELD AND SOIL WATER WHEN RECLAIMING SODIC MINESPOIL[1]

by

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Abstract. Minespoil sodicity has the potential to impede reclamation success on surface mined-land. A joint government/coal industry experiment was established near Highvale, Alberta to determine suitable subsoil thicknesses (0, 55, 95, 135, 185 and 345 cm underlying 15 cm topsoil) for reclaiming sodic minespoil and maximizing production of an annual barley (*Hordeum vulgare* L.) cereal crop or a perennial alfalfa-smooth bromegrass (*Medicago sativa* L., *Bromus inermis* Leyss.) forage mixture. Barley and forage yields were lower on the 0 cm subsoil treatment than all other treatments. Yields for both crops increased as subsoil thickness increased to 55 cm. There was a consistent trend toward optimum yields on the 95 cm subsoil treatment, but the difference between 55 and 95 cm was not significant. The replacement of 55 to 95 cm subsoil plus 15 cm topsoil appeared sufficient to restore post-mine productivity to the potential achieved on surrounding agricultural land. Root depth under the forage mixture increased as total soil thickness increased, while increases under the cereal were not generally significant. The average effective root zone extended to about 85 cm under barley and 185 cm under alfalfa-smooth bromegrass. Average seasonal soil water within the effective subsoil root zone generally increased under barley and decreased under alfalfa-smooth bromegrass over time. Accumulations of soil water above the subsoil/minespoil interface under barley were attributed to lower consumptive use of available soil water and a shallower effective root zone compared to forage. Perennial forages appeared to be more effective in reducing soil water accumulations above the interface and promoting reclamation success of sodic minespoil.

Introduction

More than half of the coal recoverable by strip-mining in North America underlies the Northern Great Plains of Canada and the United States (Currie 1981). Research in the Plains region has shown that water infiltration/retention and sodicity/soluble salt levels are two important soil properties that can be modified during reclamation (Doll et al. 1984). When minespoil has properties that restrict plant growth and impede reclamation success, sufficient topsoil and/or subsoil should be salvaged and replaced to restore post-mine productivity (Hargis and Redente 1984). Chemical reclamation has proven effective, but does not have the physical benefits of soil replacement (Doering and Willis 1975).

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Minespoil sodicity causes clay particles to become dispersed, reducing pore size and restricting movement of air and water (Smith et al. 1985; Uresk and Yamamoto 1986). Upward migration of sodium can deteriorate the quality of overlying topsoil or subsoil and contribute to declining productivity (Merrill et al. 1980). Accumulations of sodium have been observed immediately above the minespoil contact (Merrill et al. 1983b; Scholl 1987). Reduced permeability at the minespoil contact can also contribute to accumulations of soil water. Higher water content increases the efficiency of upward sodium movement, such as by chemical diffusion or convection (Merrill et al. 1983a). It also has the potential to reduce surface access by farm machinery if accumulations of soil water persist.

The benefits of topsoil replacement over sodic minespoil have been shown to increase crop yields and improve water use efficiency with the soil profile (Halvorson et al. 1987; Redente et al. 1982; Sieg et al. 1983). Merrill et al (1983a) showed that an application of 30 cm of topsoil over moderately and highly sodic minespoil increased forage yields by 25% and 84%, respectively, compared to only an 8% increase over non-sodic minespoil. Subsoil underlying topsoil has also proven beneficial in reclaiming sodic minespoil and restoring productivity (Pedology Consultants Ltd. 1987; Power et al. 1979). Barth and Martin (1984) showed that about 70 cm total soil thickness over sodic minespoil provided maximum perennial grass yields. Power et al. (1981) reported an increase in yield and root depth for several crops as subsoil thickness increased. Results showed that when sodic minespoil was within 90 and 150 cm of the surface, water extraction under alfalfa was to 135 and 175 cm, respectively; under crested wheatgrass (Agropyron desertorum) it was to 120 and 150 cm, respectively; water extraction under native grasses was to 80 and 120 cm, respectively; and water extraction under spring wheat (Triticum aestivum L.) was to 75 and 95 cm, respectively. Merrill et al. (1985) and Power et al. (1985) reported maximum perennial grass yields on 20 cm topsoil plus 80 cm subsoil over sodic minespoil. They indicated that both root depth and water use efficiency increased as subsoil thickness increased. It was suggested that low hydraulic conductivity in the minespoil had an inhibitory effect on plant growth by limiting water use.

Coal mines in central Alberta frequently disturb sodic material which cannot be reclaimed to acceptable standards without replacement of salvaged topsoil and subsoil. A series of experimental plots were set up to identify suitable thicknesses of subsoil replacement for reclamation that would provide equivalent productive potential to pre-mine conditions. The determination of an optimum thickness for soil replacement over sodic minespoil was also considered important due to the substantial reclamation cost. This paper reviews the effect of subsoil thickness over sodic minespoil on the productivity of selected crops, root zone activity and soil water content (Graveland et al. 1988).

Methods and Materials

The study area was in central Alberta, approximately 65 km west of Edmonton (114° 34' Lat., 53° 29' Long.). Sodic minespoil in the Highvale Mine region originated from Dark Gray Solodized Solonetz and Solonetzic Dark Gray Luvisols that were developed on weathered residual bedrock and glacial till (Canada Soil Survey Committee 1978). The area has a sub-humid to humid climate, averaging 504 mm of precipitation annually (Environment Canada 1982). Growing season (April-October) precipitation was 326 mm in 1983, 428 mm in 1984, 411 mm in 1985, 506 mm in 1986 and 382 mm in 1987. Rainfall across the growing season generally followed a normal distribution, peaking in July. The growing season consists of about 104 frost-free days. The mean daily temperature during the growing season was 11.4°C in 1983, 10.7°C in 1984, 10.6°C in 1985, 11.2°C in 1986 and 12.3°C in 1987.

A series of plots were established on levelled minespoil at the Highvale mine in 1982. The experimental design had six subsoil thicknesses randomized in main-plots, two crops randomized in split-plots and three replications of each treatment. Main-plots included subsoil thicknesses of 0, 55, 95, 135, 185 and 345 cm underlying 15 cm of topsoil. Split-plots were seeded to an annual six-row barley (Hordeum vulgare L. cv. 'Klondike') crop or a perennial alfalfa-smooth bromegrass (Medicago sativa L. 'Rambler', Bromus inermis Leyss. 'Carlton') forage mixture.

Each main-plot measured 16 m wide X 20 m long. Plots were excavated into the minespoil to the required depth and the exposed sides lined with plastic to restrict lateral movement of water and sodium. Subsoil (mixed B and C horizons) was added and packed by a small front-end loader until level with the surface, then topsoil (A horizon) was applied. The experimental area was graded to allow drainage away from each plot. Non-sodic topsoil and subsoil material (Dark Gray Luvisol) was salvaged from an unmined field adjacent to the mine area. The chemical and physical characteristics of the topsoil, subsoil and minespoil materials are shown in Table 1. Samples were air dried and pH, EC, SAR, and soluble Na, K, Ca, Mg, Cl and SO_4 were determined by saturated paste extract (McKeague 1978). A 3-point determination of texture was made by hydrometer.

Two neutron probe access tubes were installed in each split-plot to a depth 50 cm below the subsoil/minespoil interface (Howse 1981). Soil water (% by volume) was measured with a Campbell Pacific Model 501 Nuclear Depth Probe. Soil water measurements were conducted at 15 cm intervals once a month during the 1983 to 1987 growing seasons (April to October).

Barley was drilled-seeded in May of each year at a rate of 108 kg/ha. Fertilizer was applied annually at rates of 17 to 75 kg N/ha and 0 to 17 kg P/ha. Alfalfa and smooth bromegrass were seeded with a Model SST 1201 Brillion seeder in June, 1983 at rates of 8 and 20 kg/ha, respectively. Fertilizer was applied annually at rates of 28 to 56 kg/ha, 11 to 17 kg P/ha and 0 to 9 kg S/ha. All fertilizer applications were made on the basis of spring soil fertility tests. Annual weed growth was controlled as required by hand weeding and herbicide application.

Crop yields were determined by clipping two randomly selected 1-m2 areas from the central portion of each split-plot at 5 cm above ground level. Annual forage samples were clipped from the same areas in late June to early July and again in mid September. Forage material was oven dried at 30°C for 48 hours and weighed. Forage establishment in 1983 and a dry fall in 1984 allowed only one harvest during these years. Grain samples were clipped in early September, air dried, threshed and weighed. In 1984, grain yields on the 0 cm subsoil treatment were reduced somewhat by geese depredation. After the fall harvest, the topsoil, subsoil and minespoil was sampled at 15- to 30-cm increments for chemical and physical analyses. Samples were air dried and analyzed in the same manner as the soil samples collected for plot construction (Alberta Soils Advisory Committee 1987). Root depth was noted from soil cores extracted during the 1985, 1986 and 1987 soil sampling program. The maximum depth of root penetration was measured along with the actual depth of topsoil and subsoil.

Yield, soil water and root data were analyzed statistically using a split-plot analysis of variance procedure for the years 1983 to 1987 (Steel and Torrie 1980). A Duncan's multiple range test was used to compare differences among treatments and years.

Results and Discussion

Crop Yields

The 5-yr mean barley (grain) and alfalfa/smooth bromegrass yields on the 0 cm subsoil treatment were lower than other subsoil treatments (Table 2). Generally, annual yields increased as subsoil thickness increased to 55 cm. There was a consistent trend toward optimum yields of barley and alfalfa/smooth bromegrass on the 95 cm subsoil treatment, but the difference between 55 and 95 cm was not significant. The 5-yr mean yields for barley (318 g/m2) and alfalfa-smooth bromegrass (478 g/m2) on the 95 cm subsoil treatment compare favorably with average 10-yr (1978-1987) barley (230 g/m2) and hay (470 g/m2) yields reported for the surrounding agricultural area (personal communication, March 7, 1988, Keir Packer, Crop Statistician, Alberta Agriculture). The results suggest that post-mine productivity can be restored by replacing 55 to 95 cm of subsoil plus 15 cm topsoil over sodic minespoil. Similar results were obtained by Barth and Martin (1984), with maximum production of a perennial grass obtained on 71 cm of replacement material. Power et al. (1981) recommended 70 cm subsoil plus 20 cm topsoil to maximize yields of several perennial and annual crops. Doll et al. (1984) suggested 60 to 90 cm subsoil plus 15 cm topsoil to maximize productivity on moderately sodic (SAR=10 to 20) minespoil.

Root Depths

Mean 3-yr root depths under barley were not significantly different among subsoil treatments, but a trend toward increasing root depth was observed when total soil thickness increased from 0 to 110 cm (Table 3). Root depths under alfalfa-smooth bromegrass, however, significantly increased as total soil sickness increased from 0 to 200 cm. Based on root depth observations and soil water measurements, the average effective root zone for barley was estimated at about 85 cm. The average effective root zone for alfalfa-smooth brome was estimated at about 165 cm in 1985, 175 cm in 1986 and 185 cm in 1987. Hausenbuiller (1985) reported a similar effective root zone for small grains (90 cm) and alfalfa (180 cm).

Penetration of barley roots from subsoil into underlying sodic minespoil was not generally observed, except in the 0 cm subsoil treatment (average penetration of 24 cm). Penetration of alfalfa-smooth bromegrass roots into sodic minespoil was observed in the 0, 55, 95 and 135 cm subsoil treatments in 1987 (average penetration of 45, 17, 26 and 6 cm, respectively). Root penetration into sodic minespoil was generally greater than the 10 cm reported by Barth and Martin (1984), but less than the 30 to 90 cm reported by Power et al. (1981). Root penetration into minespoil will likely contribute to improved infiltration of soil water and reduce bulk density over time.

Soil Water

Average seasonal soil water content within the effective subsoil root zone tended to increase over time under some subsoil treatments seeded to barley and decrease over time under some subsoil treatments seeded to alfalfa-smooth bromegrass (Table 4). The results suggest greater consumptive use of available soil water by perennial forages than annual cereals. Stoskopf (1981) reported consumptive use of soil water to be about 30% higher in alfalfa than barley. By 1987, soil water content under barley was greater than under alfalfa-smooth brome in the topsoil (26 vs. 20%), subsoil (35 vs. 28%) and minespoil (35 vs. 32%) materials across all treatments. There was a tendency towards lower soil water under forage than barley from topsoil to minespoil throughout the growing season.

Accumulations of soil water immediately above the subsoil/minespoil interface occurred less frequently in subsoil treatments under forage than under barley (Table 5). Soil water content under forage was consistently lower above the interface of the 55, 95 and 135 cm subsoil treatments in 1984, 1985 and 1986, as well as the 185 cm treatment in 1987. There was no change in soil water content above the interface for any subsoil treatment under barley. These results reflect the deeper effective root zone under alfalfa-smooth bromegrass and its higher consumptive use of soil water. Merrill et al. (1985) determined that the reduced capacity of minespoil to accept water infiltration leads to soil water accumulations above the subsoil/minespoil interface.

Occasionally, soil water accumulations above the interface under barley resulted in saturated conditions. Persistent accumulations of soil water could make access by farm equipment difficult when the minespoil interface occurs near the surface. In addition, accumulations of soil water above the interface could increase the opportunity for upward movement of soluble sodium from sodic minespoil into overlying material.

Summary and Conclusions

The application of between 55 and 95 cm of subsoil appears sufficient to restore post-mine productivity and promote optimum yields, provided appropriate crops are grown. The use of a perennial alfalfa-smooth bromegrass forage crop, rather than an annual barley crop, reduced the accumulation of soil water above the less permeable subsoil/minespoil interface, thereby reducing the potential for upward migration of sodium and improving surface access. In addition, forage root activity in the minespoil will likely encourage infiltration of soil water, reduce soil bulk density and generally improve reclamation success.

The accumulation of soil water under barley predisposes the subsoil to this possibility. It was not known if the subsoil would deteriorate and become less productive over longer periods of time due to upward migration of sodium from underlying sodic minespoil if barley rather than alfalfa-smooth bromegrass was grown.

Acknowledgements

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Table 1. Properties of topsoil, subsoil and minespoil materials used for plot construction in 1982.

Soil Property	Topsoil	Subsoil	Minespoil
Texture+	CL	SiC	SCL
pH	7.2	7.7	8.5
Saturation (%)	57	57	95
EC (dS/m)	0.64	0.51	1.89
Soluble Na (mmol/kg)	0.34	0.51	13.70
Soluble K (mmol/kg)	0.50	0.17	0.30
Soluble Ca (mmol/kg)	5.23	3.81	2.09
Soluble Mg (mmol/kg)	1.27	1.05	0.51
Soluble Cl (mmol/kg)	0.30	0.18	0.18
Soluble SO_4 (mmol/kg)	0.90	0.86	20.33
SAR	0.38	0.65	20.14

+ CL=Clay Loam SiC=Silty Clay SCL=Sandy Clay Loam

Table 2. Dry weight (g/m^2) of barley (grain) and forage (alfalfa/smooth brome) as affected by subsoil thickness.

Subsoil Thickness	1983	1984	1985	1986	1987	5-yr Mean
(cm)			Barley			
0	112 b*	7 b	154 b	197 b	205 c	135 b
55	284 a	149 a	401 a	305 a	250 bc	278 a
95	293 a	176 a	462 a	336 a	323 a	318 a
135	344 a	188 a	455 a	276 a	313 ab	315 a
185	327 a	176 a	453 a	342 a	291 ab	318 a
345	318 a	171 a	381 a	331 a	291 ab	298 a
SE	37	42	54	47	33	23
			Forage			
0	68 c	384 a	423 a	467 a	264 b	321 b
55	146 b	483 a	524 a	473 a	486 a	422 a
95	186 a	640 a	516 a	533 a	513 a	478 a
135	125 b	597 a	553 a	530 a	529 a	467 a
185	136 b	597 a	552 a	556 a	509 a	470 a
345	136 b	572 a	501 a	531 a	494 a	447 a
SE	22	98	68	70	75	42

* Means down the same column (within subtables) followed by the same letter are not significantly different at the 10% level.

Table 3. Root depth (cm) of barley and forage (alfalfa/smooth brome) as affected by soil thickness.

Total Soil Thickness	Average Interface Depth	1985	1986	1987	3-yr Mean
(cm)	(cm)		Barley		
15	15	40 a*	37 a	40 b	39 a
70	68	45 a	47 a	55 ab	49 a
110	99	58 a	58 a	66 a	61 a
150	145	60 a	58 a	61 ab	60 a
200	205	67 a	65 a	78 a	70 a
360	367	63 a	58 a	69 a	63 a
SE		12	12	12	10
			Forage		
15	15	50 c	60 e	60 d	57 e
70	76	63 c	82 de	93 c	79 d
110	107	95 b	102 cd	133 b	110 c
150	140	154 a	129 bc	146 b	143 b
200	208	163 a	170 a	146 b	159 a
360	371	158 a	159 ab	179 a	166 a
SE		12	17	13	8

*Means down the same column (within subtables) followed by the same letter are not significantly different at the 10% level.

Table 4. Changes in seasonal (April-October) soil water content (%) over time within the effective subsoil root zone under barley and forage (alfalfa/smooth brome).

Year	Effective Subsoil Root Zone	Subsoil Thickness				
		55cm	95cm	135cm	185cm	345cm
	(cm)	Barley				
1983	15-70	30.7 b*	31.2 a	30.3 a	30.9 a	31.0 b
1984	15-85	29.4 c	28.5 a	27.3 a	29.2 a	28.7 c
1985	15-85	32.8 a	32.5 a	31.7 a	33.1 a	33.8 a
1986	15-85	33.2 a	33.5 a	32.2 a	33.2 a	34.0 a
1987	15-85	33.0 a	33.8 a	32.9 a	33.9 a	34.2 a
SE		0.52	0.51	0.32	0.39	0.40
		Forage				
1983	15-115	31.6 a	31.8 a	31.2 a	31.8 a	32.0 a
1984	15-155	26.4 a	25.4 b	25.4 b	27.0 a	27.5 a
1985	15-165	25.9 a	25.0 b	24.7 bc	27.2 a	29.4 a
1986	15-175	27.3 a	26.1 b	24.0 cd	26.4 a	28.3 a
1987	15-185	26.0 a	25.1 b	22.9 d	25.5 a	27.5 a
SE		0.52	0.76	0.71	0.36	0.44

*Means down the same column (within subtables) followed by the same letter are not significantly different at the 10% level.

Table 5. Comparison of seasonal (April-October) soil water content (%) immediately above the subsoil/minespoil interface among subsoil treatments under barley and forage.

Total Soil Thickness	Sample Depth	1983	1984	1985	1986	1987
(cm)	(cm)	Barley				
70	55-70	31.6 a*	29.7 a	33.2 c	33.7 a	34.1 a
110	95-110	32.4 a	30.3 a	34.5 bc	34.1 a	36.4 a
150	135-150	32.6 a	31.5 a	35.7 b	35.5 a	38.3 a
200	185-200	29.6 b	30.3 a	33.1 c	32.3 a	35.1 a
360	345-360	33.3 a	32.2 a	38.0 a	35.9 a	37.7 a
SE		0.89	1.27	1.15	1.29	1.57
		Forage				
70	55-70	32.2 a	26.7 b	26.3 b	27.3 b	26.4 c
110	95-110	32.3 a	27.4 b	27.6 b	26.4 b	26.6 c
150	135-150	34.4 a	26.7 b	25.2 b	24.9 b	24.6 c
200	185-200	33.5 a	32.5 a	36.2 a	32.7 a	30.9 b
360	345-360	31.8 a	32.0 a	37.7 a	35.2 a	36.5 a
SE		0.77	1.31	1.57	1.93	1.90

*Means down the same column (within subtables) followed by the same letter are not significantly different at the 10% level.

THE USE OF BOTTOM ASH AS A PHYSICAL AMENDMENT TO SODIC SPOIL[1]

by

S. Landsburg[2]

Abstract. The objectives of this study were to determine the best rate and method of application of bottom ash to sodic spoil in terms of reducing the effects of excess sodium and promoting vegetative growth. Plots were set up as a randomized complete block design and the depths of bottom ash tested were 10, 20 and 30 cm. Ash was incorporated into the spoil surface using a disc, chisel plow and Kellough subsoiler. As a fourth method, ash was left as a blanket on top of the spoil. Results showed the best rate of ash to be 30 cm and the best method of incorporation to be subsoiling. Both increased moisture movement downwards and decreased soil strength values which promoted leaching, germination and root growth. The 30 cm rate also improved the chemistry of the surface 15 cm of the spoil and increased yield. All the methods plus the 20 and 30 cm rates produced toxic levels of plant available boron in the soil. The soil concentrations were not reflected in any plant toxicity symptoms.

Introduction

Since the passing of the Land Surface Conservation and Reclamation Act in 1973 in Alberta, Canada, reclamation activities have been undertaken in areas mined and abandoned before 1963 when there were few reclamation regulations. One area requiring information regarding reclamation was that of sodic mine spoil. Hence reclamation plots were initiated in 1981 on mine spoil at the Vesta Mine near Halkirk, Alberta.

Shaneman and Logan (1978) found that a surface 4 to 15 cm application of bottom ash to sodic spoil promoted forage growth. The bottom ash greatly improved the penetration of water, air and roots, and eliminated surface crusting. The authors felt that the loose, coarse-textured properties of the ash, combined with the excellent moisture-holding properties, were largely responsible for the success of the plots. Lutwick et al. (1981) found bottom ash to increase plant available boron, decrease surface crusting, increase water infiltration and increase soil salinity on sodic mine spoil materials.

Boron toxicity in plants is often associated with bottom ash amended spoil in greenhouse studies, as the ash contains extractable boron in quantities which are normally toxic to plants. Barley grown in bottom ash in a greenhouse study exhibited boron toxicity symptoms (brown spotting near leaf tips). However, in field plots barley did not exhibit toxicity symptoms and headed out normally. Preliminary evidence indicated that boron

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was washed from the ash into the spoil in field conditions, diluting the element to non-toxic levels (Shaneman and Logan 1978). Lutwick et al. (1981) also found bottom ash to increase the amount of plant available boron in soil and noted boron toxicities on barley plants grown in the greenhouse. The statement was made that if internal drainage could be improved with ash addition then the problem of boron availability would be temporary.

Although initial work in the utilization of bottom ash has provided positive trends as a surficial amendment to sodic spoil, its use is not without some problems. Due to the coarse texture of the bottom ash and its high water-holding capacity, seeding and fertilizing operations are difficult (Natsukoshi 1981). In order to minimize these difficulties, seeding and fertilizing is conducted in either early spring or late autumn, when the surface is frozen but snow cover is lacking.

The objectives of this study were to determine the best rate and method of application of bottom ash as a physical amendment to sodic spoil in terms of reducing the effects of excess sodium and promoting vegetative growth.

Materials and Methods

Experimental Design

The plots were set up in a randomized complete block design (Fig. 1). Each plot measured 10 m by 20 m and was separated from neighbouring plots by a 2 m buffer zone. There were three replicates consisting of 12 plots each. Each replicate was separated by a 10 m buffer zone. The three rates of bottom ash tested were 10, 20 and 30 cm. Ash was incorporated into the spoil surface using a disc, chisel plow, and Kellough subsoiler. As a fourth method, ash was left as a blanket on top of the spoil.

Seeding and Fertilizing

All plot construction activities were completed by December 1981. Each

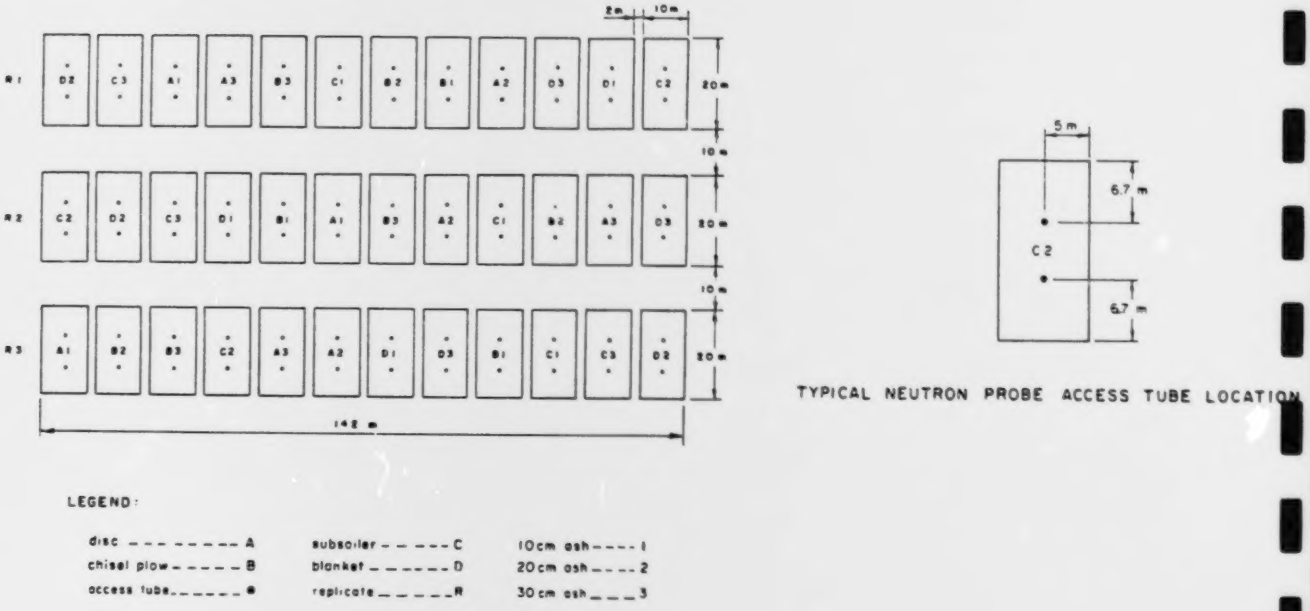
2m
10m
R1
D2
C3
A1
A3
B3
C1
B2
B1
A2
D3
D1
C2
20m
10m
R2
C2
D2
C3
D1
B1
A1
B3
A2
C1
B2
A3
D3
20m
10m
R3
A1
B2
B3
C2
A3
A2
D1
D3
B1
C1
C3
D2
20m
142 m
5 m
6.7 m
C2
6.7 m
TYPICAL NEUTRON PROBE ACCESS TUBE LOCATIO
LEGEND:
disc ——————— A
chisel plow ————— B
access tube ————— ●
subsoiler ———— C
blanket ————— D
replicate ————— R
10cm ash ———— 1
20cm ash ———— 2
30cm ash ——— 3

Figure 1.
Experimental design of the bottom ash plots and location of the neutron probe access tubes.

plot was hand-sown using a cyclone seeder in May 1982. A seed mixture comprised of Fairway Crested Wheatgrass, Tall Wheatgrass, Sodar Streambank Wheatgrass and Rambler Alfalfa (coated and pre-inoculated) was applied at a rate of 0.5 kg/plot. A fertilizer blend of 19% 11-51-0, 58% 34-0-0, and 23% 0-0-60 was also hand broadcast onto each plot at a rate of 6 kg/plot.

Soil Sampling and Analyses

Soil samples were taken in the fall of 1983, 1984 and 1985. Samples were taken in 15 cm increments from the surface to 90 cm. Two subsamples per increment were mixed and bagged. Procedures used for the soil analyses are those outlined by McKeague (1978) as follows: pH (in water); EC (saturation extract); soluble salts (saturated paste extract); NH4 and NO3 (2N KCL); PO4 (0.03N NH4F and 0.03N H2SO4); K (NH4OAc at pH 7); B (hot water extractable); and total C (dry combustion).

A Campbell Pacific 501 neutron probe was used to monitor soil moisture on a monthly basis. Two access tubes per plot were installed to a depth of 1.5 m in order to monitor moisture in 15 cm increments from 0 to 120 cm (Fig. 1). The access tubes had the following specifications: 1.67 m long, an outside diameter of 5 cm, and an inside diameter of 4.8 cm. An aluminium plate was welded to one end of each tube to prevent movement of water into the tube.

A Mark 1 Model Bush Recording Soil Penetrometer was used to measure soil strength in 1985 only. Fifteen measurements were taken in 3.5 cm intervals from 0 to 52.5 cm. Ten replicates were taken from each plot.

Plant Sampling and Analyses

A small plot-size Jari mower was used to cut down the vegetation on the plots each fall (1983 to 1985) leaving a 15 cm stubble. The harvested material from each plot was then raked and weighed on site to obtain a wet weight. One composite sample was taken at random from each plot. Plant analyses included N, P, K, Ca, Mg, and B, and were done using a HNO3-HClO4 extraction. An atomic adsorption spectrophotometer was used for the elemental analyses.

Statistical Analyses

The soil and plant variables were statistically analyzed over years and depths using a split-plot model by incorporating years and depths as split-plot factors (Steel and Torrie 1980). Statistical analyses were also done for each year with depth incorporated as a split-plot factor, and for each year at each depth. Trend analyses were performed for quantitative factors, and Tukey's test was used to evaluate significant differences between means.

In order to make the statistical analyses of the moisture data manageable, the monthly moisture observations were averaged to produce one moisture value for each plot for each of four seasons: spring (March, April, May), summer (June, July, August), fall (September, October, November), and winter (December, January, February). The moisture data were then analyzed in the same way as the soil and plant variables. Only the summer data will be discussed in this report as the trends were similar for each season.

Only those parameters significantly affected ($p<0.05$) by either method, rate, year, depth or any subsequent interactions will be discussed. When interpreting the results, unless a specific year is mentioned, there is no significant difference between years. When changes in parameters are discussed between increments, the depth used represents the lowest depth of a 15 cm increment.

Results

Soil Chemistry

Saturation Percentage (sat.%). Method of ash application affected the sat.% at depth in 1984 only (Fig. 2). The sat.% was lowest within the surface 15 cm for all methods, but increases occurred at different depths. Values significantly increased at: 30 cm using the disc; 15 cm using the chisel plow; 30 cm using the subsoiler; and 15 cm applying the blanket. Rate of ash application affected the sat.% at each depth monitored (Fig. 3). The 20 and 30 cm rates reduced the sat.% within the 0 to 15 cm depth compared to the 10 cm rate, but only the 30 cm rate decreased it within the remaining depths. Values for sat.% were not significantly different for the 10 and 20 cm rate below 15 cm. In general, the sat.% increased from the soil surface down to 90 cm for each rate and method of ash application.

pH. Values for pH decreased with increased rates of ash. Mean values were 8 for the 10 cm rate, 7.9 for the 20 cm rate and 7.8 for the 30 cm rate. Regardless of the rate or method of ash application, pH changed with depth in the plots. The pH increased from the soil surface (7.8) down to 45 cm (8.0), remained the same at 60 cm, and then decreased down to 90 cm (7.9) to values which were not significantly different than those within the surface 30 cm. These changes in pH were statistically different but not chemically or biologically significant.

Electrical Conductivity (EC). There were differences in values for EC between rates of ash at the 0 to 15, 60 to 75, and 75 to 90 cm depths (Fig. 4). Within the surface 15 cm, the EC decreased as the rate of ash increased. Values in mS/cm were 4.7 (10 cm), 3.8 (20 cm), and 2.3 (30 cm). The reverse occurred at the other two depths. Values for EC increased as the rate of ash increased. Mean values in mS/cm were 4.3, 5.0, and 5.8 at the 60 to 75 cm depth, and 3.8, 5.2 and 5.4 at the 75 to 90 cm depth. Values for EC decreased with increasing depth for the 10 cm rate, and increased with increasing depth for the 20 and 30 cm rates.

Soluble Calcium (Ca), Magnesium (Mg) and Sodium (Na). Both soluble Ca and Mg concentrations increased with

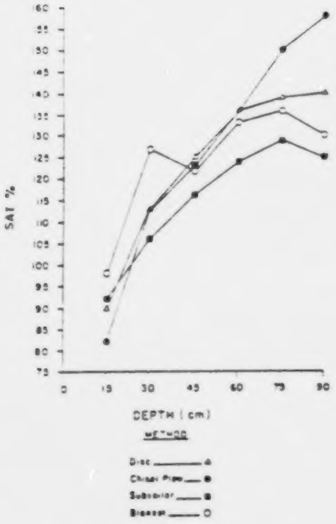

Figure 2.
Effect of method on the sat. %
at each depth in 1984.

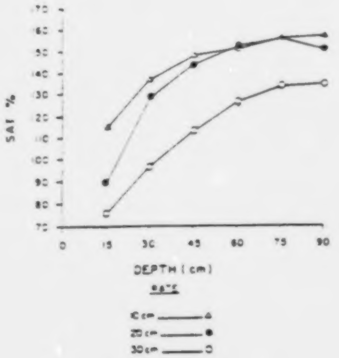

Figure 3.
Effect of rate on the sat. %
at each depth.

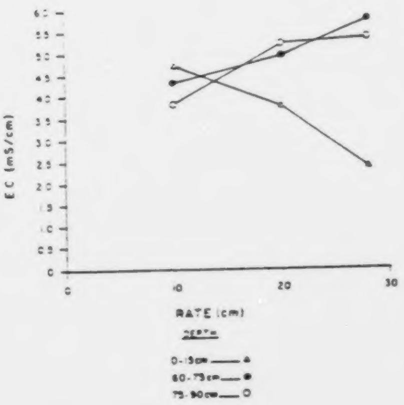

Figure 4.
Effect of rate on the EC
at various depths.

increasing rates of ash at the 60 to 75 and 75 to 90 cm depths (Fig. 5). Concentrations of Ca in meg/L with increasing rates of ash were 2.6, 4.7 and 6.3 at the 60 to 75 cm depth, and 1.9, 5.4 and 6.0 at the 75 to 90 cm depth. Corresponding concentrations of Mg in meg/L were 1.1, 1.7 and 2.2 at the 60 to 75 cm depth and 0.7, 2.2 and 2.2 at the 75 to 90 cm depth.

Concentrations of soluble Na decreased within the 0 to 15 cm depth, and increased within the 75 to 90 cm depth with increasing rates of ash (Fig. 5). Concentrations in meg/L with increasing rates were 54.3, 42.0 and 25.0 within the surface 15 cm and 43.0, 56.7 and 61.1 at the 75 to 90 cm depth.

For each of the soluble cations, concentrations decreased from the soil surface down to 90 cm for the 10 cm rate, and increased down to 90 cm for the remaining rates.

Sodium Adsorption Ratio (SAR). In 1983 and 1985, the SAR decreased with increased rates of ash at the 0 to 15 and 15 to 30 cm depths (Fig. 6). Values in 1983 with increasing rates were 40, 23 and 14 at the 0 to 15 cm 30 cm depth. In 1985 values were 32, 30, 19, and 39, 34, and 29 respectively. In 1984 concentrations at all depths decreased in a linear fashion with increasing rates. Mean values were 41.5, 39.1 and 33.6. For each rate of ash, the SAR increased from the soil surface down to 90 cm.

Soluble Sulphate (SO_4). Sulfate concentrations were affected by the different rates of ash at the 0 to 15, 45 to 60, 60 to 75 and 75 to 90 cm depths. With increasing rates of ash, SO_4 decreased in a linear fashion within the surface 15 cm (Fig. 7). Concentrations were 48.1, 35.4 and 21.9 meg/L respectively. Below 45 cm, SO_4 concentrations increased in a linear fashion with increasing rates of ash. Concentrations in meg/L were 46.1, 57.8 and 61.2 at 45 to 60 cm; 44.0, 51.1 and 59.8 at 60 to 75 cm; and 38.5, 55.1 and 56.1 at 75 to 90 cm.

Concentrations of SO_4 decreased from the soil surface down to 90 cm for the 10 cm rate, and increased from the soil surface down to 90 cm for the 20 and 30 cm rates.

Soluble Boron (B). Of the three years monitored, concentrations of plant available B were highest in 1983 within the surface 30 cm (Fig. 8). Values in ppm were 12.23 in 1983 and a mean value of 5.64 in 1984 and 1985 for the 0 to 15 cm depth. Within the 15 to 30 cm depth concentrations were 6.39 in 1983 and a mean value of 3.48 in 1984 and 1985.

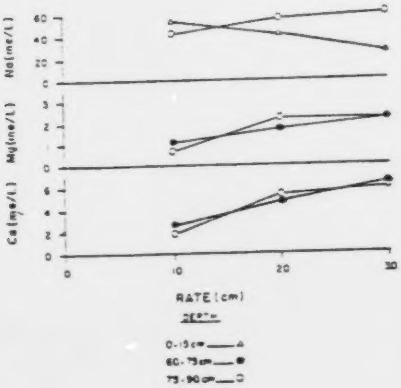

Figure 5.
Effect of rate on soluble Ca, Mg and Na at various depths.

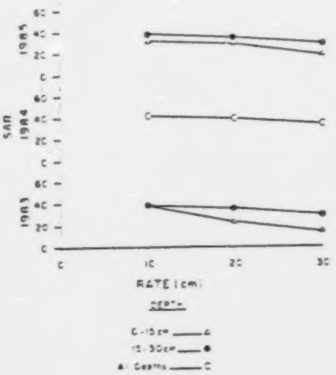

Figure 6.
Effect of rate on the SAR at various depths.

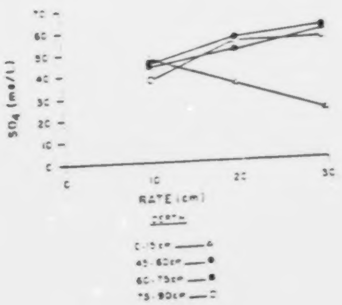

Figure 7.
Effect of rate on SO_4 concentrations at various depths.

B concentrations were higher in 1983 (8.12 ppm) than either 1984 or 1985 (3.72 ppm) for the 30 cm rate, and higher in 1983 (3.18 ppm) than 1985 (1.63 ppm) for the 20 cm rate.

Within the 0 to 15, 15 to 30 and 30 to 45 cm depths, concentrations of B increased with increased rates of ash (Fig. 9). Concentrations in ppm for the 10, 20 and 30 cm rates at each depth were: 3.94, 6.84, and 12.73 (0 to 15 cm); 1.72, 2.66, and 8.97 (15 to 30 cm); and 1.24, 1.77, and 3.86 (30 to 45 cm). In general, B concentrations decreased with increasing depth for each rate of ash.

Within the surface 15 cm, concentrations of B were lowest for the chisel plow method (5.56 ppm) and highest for the blanket method (10.44 ppm). The disc had lower B concentrations (6.99 ppm) than the blanket method, and the subsoiler had higher concentrations (8.36) than the chisel plow. Concentrations of B were highest within the surface 15 cm for each method, but the depth at which concentrations became significantly lower differed for each method. The depths were 15 cm for the disc and blanket, and 30 cm for the subsoiler and chisel plow. In general, concentrations of B decreased with increasing depth for each method.

Percent Organic Matter (%OM). In 1985 %OM was highest (10.5%) as compared to 1983 or 1984 (6.5%) which were not significantly different. The amount of OM also increased with increased rates of ash. Values in percent were 5.6, 6.3 and 11.8 for the 10, 20 and 30 cm rates.

Soil Strength

Method of ash application had no effect on soil strength within the surface 21 cm or depths below 45.5 cm (Table 1). Between 21 and 45.5 cm the subsoiler resulted in lower soil strengths than the disc, and between 24.5 cm and 42 cm it produced values lower than the chisel plow. From 35 to 45.5 cm the blanket method produced lower soil strengths than the disc and chisel plow methods. Therefore, in order of decreasing soil strengths between 21 and 45.5 cm the methods were rated as disc and chisel plow (0.34 bar), blanket (0.29 bar) and subsoiler (0.20 bar).

Rate of bottom ash had no effects on the surface 3.5 cm or depths below 49 cm. Between 3.5 and 49 cm, soil strength decreased with increased rate of ash (Fig. 10). In general, the soil strength decreased from 0.31 bar at the 10 cm rate, to 0.27 bar at the

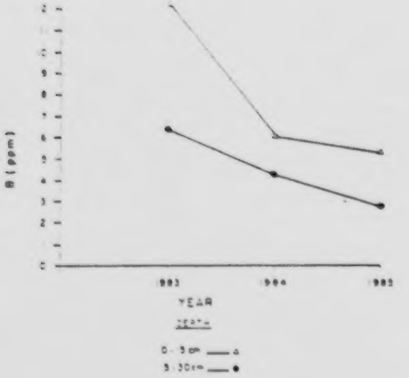

Figure 8.
Effect of year on B concentrations at various depths.

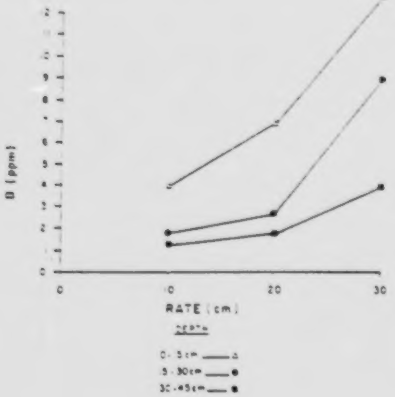

Figure 9.
Effect of rate on B concentrations at various depths.

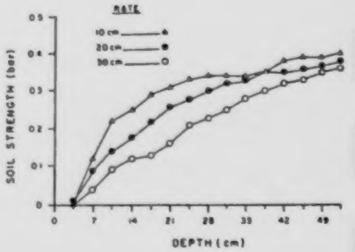

Figure 10.
Effect of rate on soil strength at depth.

Table 1. Effects of method on soil strength at each depth monitored.

	Soil Strength (bar)														
Method	3.5 cm	7 cm	10.5 cm	14 cm	17.5 cm	21 cm	24.5 cm	28 cm	31.5 cm	35 cm	38.5 cm	42 cm	45.5 cm	49 cm	52.5 cm
disc	0.00 a	0.08 a	0.16 a	0.20 a	0.24 a	0.27 a	0.30 a	0.31 a	0.34 a	0.36 a	0.37 a	0.39 a	0.40 a	0.40 a	0.41 a
chisel plow	0.00 a	0.08 a	0.15 a	0.18 a	0.22 a	0.25 ab	0.29 a	0.32 a	0.34 a	0.36 a	0.37 a	0.38 a	0.38 ab	0.38 a	0.39 a
subsoiler	0.01 a	0.10 a	0.14 a	0.17 a	0.19 a	0.21 b	0.23 b	0.25 b	0.26 b	0.26 b	0.28 b	0.31 b	0.33 b	0.35 a	0.36 a
blanket	0.00 a	0.08 a	0.16 a	0.18 a	0.21 a	0.25 ab	0.27 ab	0.28 ab	0.29 ab	0.30 b	0.30 b	0.31 b	0.34 b	0.35 a	0.37 a

Means with the same subscript (a,b,c) within a column are not significantly different at $p<0.05$.

20 cm rate, and to 0.21 bar at the 30 cm rate.

Soil Moisture

The only difference between methods occurred at the 30 to 45 cm depth. The blanket had the highest moisture content (MC) (33.73%) and the disc the lowest (30.24%). The chisel plow and subsoiler were similar to both the blanket and disc and had a mean MC of 33.36%. In general, each method had increasing values for MC with depth (Fig. 11).

Within the surface 45 cm, MC decreased with increasing rates of ash (Fig. 12). Values in percent for increasing rates of ash were: 17.94, 14.96 and 10.26 (0 to 15 cm); 30.24, 27.46 and 22.43 (15 to 30 cm); and 34.11, 31.60 and 30.79 (30 to 45 cm). Below 45 cm MC values were not significantly different until the 105 to 120 cm depth. Within this depth, the trend was reversed. Moisture percentages increased with increasing rates (35.80, 37.25 and 38.04% respectively).

Moisture was highest at all depths in 1983 as compared to 1984 and 1985 which were similar (Fig. 13).

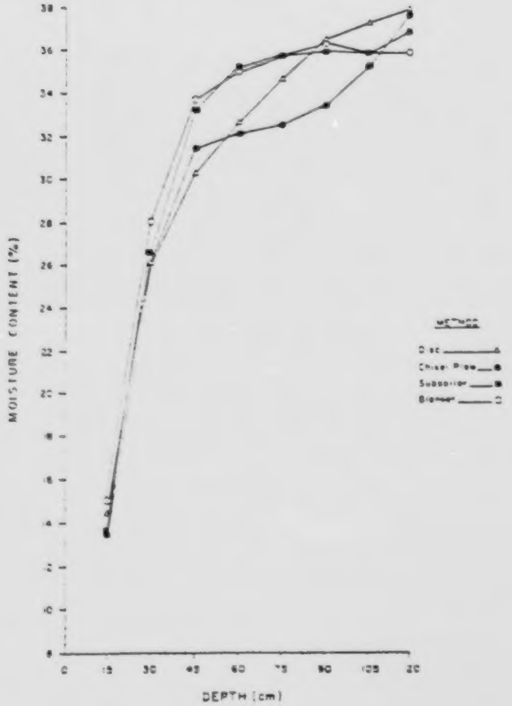

Figure 11.
Moisture content at different depths for each method.

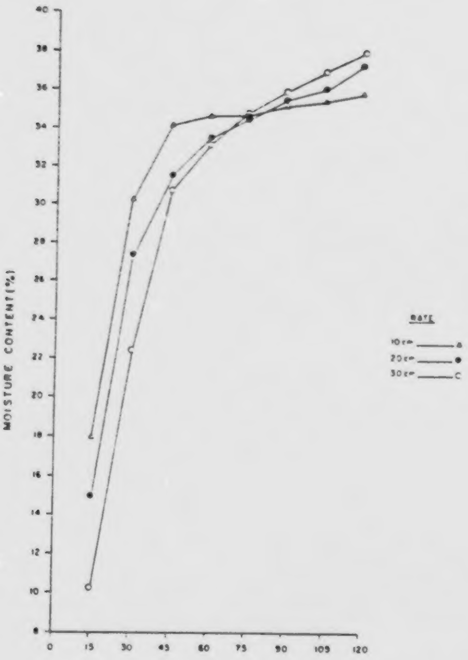

Figure 12.
Moisture content at different depths for each rate.

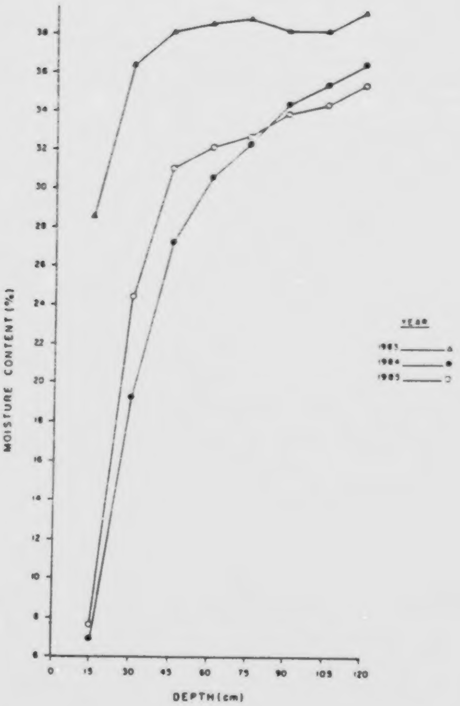

Figure 13.
Moisture content at different depths for each year.

Plant Variables

There was a significant increase in yield with increasing rates of ash. In t/ha, yields were 1.07 (10 cm), 1.41 (20 cm) and 1.82 (30 cm). Yields were lower in 1984 (1.07) than either of 1983 or 1985 (1.62) which were not significantly different from each other.

Concentrations of B increased with increasing rates of ash. Concentrations in ppm were 43.4 (10 cm), 50.0 (20 cm), and 52.3 (30 cm).

Percentages of N, P, and K were lowest in 1983 and were not significantly different in 1984 and 1985 (Fig. 14). The reverse was true for Ca and Mg. Concentrations were highest in 1983 and not significantly different in 1984 and 1985.

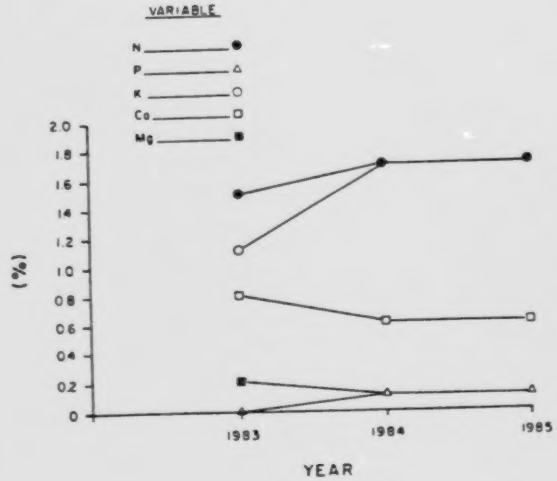

Figure 14.
Effect of year on plant variables.

Discussion

Method of Bottom Ash Application

The method of bottom ash application had few significant effects on the soil variables. The subsoiler method decreased the sat.% and increased B concentrations within the surface 30 cm of the plots. It was also the most effective method in terms of having the lowest soil strength measurements between 21 and 45.5 cm. The values for sat.% and B indicated that effective mixing of ash and spoil occurred down to a maximum depth of 30 cm. The low soil strength values indicate that the teeth of the subsoiler were able to penetrate down to 45.5 cm and loosen the spoil material.

Within the surface 15 cm the blanket method reduced the sat.% and had the highest B concentrations. Below 15 cm, this method had the second lowest soil strength measurements and had the greatest amount of moisture within the 30 to 45 cm depth. Field observations showed that moisture seemed to concentrate at the ash-spoil interface with the blanket treatments. This is confirmed by the high moisture at the 30 to 45 cm depth and reduced soil strength values. A problem with the 30 cm blanket treatment in the field was trafficability. At the higher ash rates, it was very difficult to use farm machinery to seed, fertilize and cultivate the plots.

In a similar fashion to the subsoiler, the disc method reduced the sat.% within the surface 30 cm. Unlike the subsoiler, the disc had increased B concentrations within the surface 15 cm. The disc had the highest soil strength values and had the lowest MC values at the 30 to 45 cm depth. The disc method had no effect on any of the soil parameters monitored below 30 cm. This reflects the fact that the disc is a surface tillage treatment.

The chisel plow method decreased the sat.% within the surface 15 cm and also had the lowest B concentrations within that depth. The chisel plow had increased B concentrations within the top 30 cm, and like the disc, had the highest soil strength values. The chisel plow had its greatest effect within the surface 30 cm of the plots.

As was mentioned previously, each of the methods had increased B concentrations within the surface 15 cm. Even though each method resulted in different B concentrations, all but the chisel plow had values in the toxic range of ≥5.7 ppm (Gupta et al. 1985) for plant growth. The chisel plow had values in the high range which is ≥1.5 ppm (Alberta Agriculture 1983). Concentrations of B within the surface 15 cm reflect the amount of mixing which occurred. The blanket treatment had the highest concentration and was not mixed while the chisel plow had the lowest and resulted in maximum mixing.

The method of ash application had no effect on plant yield or nutrients, therefore was not a limiting factor to plant growth.

Rate of Bottom Ash Application

The rate of bottom ash application produced the most significant effects on both the plant and soil variables. As the rate of ash increased, the chemistry of the surface 15 cm of the plots was improved. The EC along with parameters reflecting sodicity (pH, sat.%, SAR, Na_2SO_4) were decreased. Along with an improvement in chemistry was a corresponding increase in yield and OM content in the soil. Therefore, as bottom ash was increased from 10 to 30 cm, the chemistry of the surface was improved which promoted increased crop growth. In terms of yield, on a wet weight basis from 1983 to 1985 the yields averaged 1.07, 1.41, and 1.82 t/ha respectively for the 10, 20, and 30 cm rates. Yields in Census Division No. 7 (Agricultural Reporting Area 4A) within which the plots fell, reported a mean yield of 2.9 t/ha, for the same time period. Yields for each of the application rates were below those reported but increased with increasing rates of ash.

While the surface of the spoil was improved, there was an increase in

EC and corresponding soluble salts below 60 cm. Therefore, increased rates of ash promoted leaching from the soil surface down to below 60 cm. This is also seen by observing the trends in the concentrations of soluble Na, Ca, Mg and SO_4. At the 10 cm rate, concentrations decreased down to 90 cm. At the 20 and 30 cm rates, concentrations increased down to 90 cm. Values for SAR, pH and sat.% decreased at all depths with increasing rates of ash. The changes in soil moisture with changing ash rates also reflected a leaching environment. As the rates of ash increased, the moisture within the 0 to 45 cm depth decreased, and increased within the 105 to 120 cm depth. Moisture movement downwards would have been enhanced by the decreased soil strength with increased ash rates between 3 and 48.5 cm.

B concentrations increased within the surface 45 cm with increased ash rates. B was present at medium to high levels (0.8 to ≥1.5 ppm) (Alberta Agriculture 1983) using the 10 cm rate. It was at toxic levels (≥5.7 ppm) (Gupta et al. 1985) within the surface 15 cm for the 20 cm rate, and within the surface 30 cm for the 30 cm rate. Even though B was at toxic concentrations within the soil, it was not reflected in the plant analyses (Table 2). All of the micro-nutrients in the alfalfa-grass hay mixture were in the sufficient range except for Fe, which was in the high range.

Conclusions

Of the three rates tested (10, 20, 30 cm) the best rate of bottom ash to be applied to sodic spoil was 30 cm. A rate of 30 cm of bottom ash improved the chemistry, decreased the soil strength, and increased the soil moisture of the spoil. The 30 cm rate also promoted leaching as was seen by a decrease in moisture within the surface of the spoil accompanied by an increase in moisture at depth. The rate causing poorest results was 10 cm. B concentrations increased in both spoil and plant tissues as the rate of ash increased. Concentrations were at toxic levels in the soil at the 20 and 30 cm application rates, but the toxicities were never reflected in any plant toxicity symptoms.

Of the four methods tested (disc, chisel plow, subsoiler, and blanket) the best method of bottom ash incorporation into sodic spoil was

Table 2. Comparison of micronutrient concentrations in forage from the bottom ash plots and those in the Alberta literature.

Nutrient	Alberta	Range	Bottom Ash Plots	Range
% Ca	1.31[1]		0.66	
% Mg	0.25[2]		0.13	
% K	1.44[2]		1.26	
% N			1.65	
% P	0.20[1]		0.11	
B (ppm)	5.00[3]	low[3]	49.57	sufficient[3]
Cu(ppm)	7.05[2]	marginal[3]	11.42	sufficient[3]
Fe(ppm)	261.50[2]	high[3]	346.33	high[3]
Mn(ppm)	36.50[2]	sufficient[3]	38.97	sufficient[3]
Zn(ppm)	23.00[2]	sufficient[3]	48.63	sufficient[3]

[1] Alberta Agriculture 1981
[2] Alberta Agriculture 1984 and Alberta Agriculture 1985
[3] Alberta Agriculture 1983

subsoiling. The subsoiler effectively mixed ash and spoil within the surface 30 cm, and decreased the soil strength at depth. The method producing the poorest results was the disc. All of the methods resulted in B concentrations in the toxic range for plants. These toxicities never occurred in the plant tissues.

The blanket method at the 30 cm ash rate created trafficability problems which made seeding, fertilizing and cultivation of the plots very difficult. Method of bottom ash application had no effect on any of the plant variables.

Hay yields for each of the rates were below those reported for adjacent farm lands, but increased with increasing rates of ash. Rate was more important than method in terms of significant effects on plant and soil variables.

Based on the results of this study, the most appropriate method and rate of bottom ash application to sodic spoil is to topdress the spoil with 30 cm of ash and mix it in using a subsoiler.

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IMPROVEMENT OF FLY-ASH RECLAMATION WITH ORGANIC, ORGANO-MINERAL AND MINERAL AMENDMENTS[1]

by

HERIBERT INSAM[2]

Abstract. Fly-ash deposits are usually difficult to reclaim due to poor chemical and physical properties. Using different kinds of composts, organic amendments, soil conditioners, and mineral fertilizer we established a reclamation trial on an ash-dump in the Helmstedt mining area (FRG). Vitality of the grasses sown, as well as the percent plant cover were highest on the plots amended with Ferihum^R (bark compost) and Biosol^R, a product of fungal mycelium. If these organic amendments were supplemented by ACS^R, an organo-mineral complex, vitality and plant cover were improved. Microbial activity (arginine-ammonification rate) and biomass were highest on the compost plots, and lowest on those that had not received organic amendments. Supplementation with ACS^R increased microbial biomass levels. The positive effects of Biosol^R, ACS^R, and Ferihum^R, or combinations thereof, may have been due to a reduction of pH or salt concentrations in the soil solution, or an improved physical stability due to the formation of stable aggregates. Additional key words: Microbial biomass, arginine-ammonification

Introduction

Coal fired electric power plants are producing huge amounts of fuel ash. For disposal, the ash is mixed with water and the slurry is pumped into a lagoon where the ash settles and the water evaporates or is drained. Alternatively, the ash may be deposited dry in pits (Maciak and Pronczuk 1980). These dumps usually are a dusting desert, and it is highly desirable to prevent wind erosion. Preferably, this is accomplished by a rapid revegetation of the area. However, unless the area is covered with topsoil, several problems have to be resolved before vegetation may be established.

Most important, physical and chemical properties have to be improved. The water holding capacity is usually sufficient, but due to the lack of organic matter no stable aggregates are formed. This may result in compaction layers impenetrable by plant roots. This may be improved by the use of organic matter, such as mulches or composts (Bradshaw and Chadwick 1980).

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Organic substances enhance the formation of stable clay mineral complexes either directly, or by promoting soil microbial activity (Tate, 1987). Microbial biomass has successfully been used for studying reclamation by Insam and Haselwandter (1985).

The purpose of the present study was to investigate methods to improve short-term revegetation. Several fertilizers and soil conditioners, and combinations thereof, were tested for their potential to accelerate reclamation by determining their effects on soil microbial biomass and activity (arginine-ammonification rate), as well as on the response by the vegetation.

Materials and Methods

The experiments were set up on the Braunschweigische Kohlebergwerke (BKB) ash-dumps near Helmstedt, FRG. Mean annual precipitation and temperature are 640mm and 9.6°C, respectively. Two years before initiation of the trial, the ash had been dumped, and a subsequent reclamation effort had failed. The trial was started on April 17, 1986 and set up in a split plot design with two replications. Plot size was 10x10m. Three organic substrates, as well as a mineral fertilizer were applied either without further amendment, or with sulfur, ACS^R, or Alginure^R (Table 1). Control plots were also included.

The nutrient content of the ash was as follows (% of dry weight): N 0.022; Ca 5.6, Mg 0.27, K 0.28, Na 0.07, organic C 0.97. 50% of the organic C was in form of inert coal particles. The organic substrates included municipal waste compost (8mm fraction, Kompostwerke Duisburg), bark compost (*Picea abies*, Ferlhum^R, Fehring Co., Bielefeld), and dried fungal mycelium (Biosol^R, Biochemie GmbH, Kundl, Austria). ACS^R (ACS Comp., Celle) is an organo-mineral complex, Alginure^R (TILCO, Stuttgart) is a Ca-alginate. Before plot establishment, the whole area received 200kg·ha^{-1} NPK (15:15:15) fertilizer.

Table 1: Fertilizers and soil conditioners: chemical properties and application rates

	application rates (g·m^{-2})	WC (%)	OS (%)	pH	Nutrient Contents (%) N	P	K	Ca	Mg
waste compost	3600	49	65	7.2	1.4	0.7	0.4	4.0	0.6
bark compost	3600	48	70	6.1	0.1	0.02	0.2	0.1	-
Biosol^R	200	6	70	6.2	7.5	5.6	8	2	4
ACS^R	160	-	-	-	9.3	4.7	-	-	-
Alginure^R	138	55	45	9.4	0.3	-	-	-	-
Mineral fertilizer	20	-	-	-	21	-	-	-	-

WC...water content; OS...organic matter (% of dry weight)

A mixture of grasses was sown at a rate of 250kg·ha^{-1}, including *Festuca rubra* var. genuina (20%), *F. ovina* (15%), *F. tenuifolia* (30%) and *Agrostis tenuis* (15%). The seed was applied as a mixture with water and the respective amendment (ACS^R or Alginure^R). The organic substrates and sulfur were applied manually and incorporated 10cm. Two times,July 8 and Sept. 9, 1986, the area of plant cover was estimated (Braun-Blanquet, 1964). On Sept. 9, the vitality of the plants was also recorded. For soil biological analyses, soil samples from the surface 10cm were taken with a core sampler (1cm i.d.) on July 7,1986 and April 4, 1987. Each plot was divided into 4 subplots, from each of which 10 random samples were taken and bulked. The soil samples were sieved (2mm), adjusted to a water content corresponding to approx. -300kPa water tension, and stored at 4°C for up to 6 weeks.

Microbial biomass (C_{mic}) was determined with the substrate induced respiration method (SIR) (Anderson and Domsch 1978). Because of high carbonate contents, the method was modified. Instead of CO_2 production, the O_2 consumption was measured. For the calculations, a respiratory quotient of 1 was used, following C_{mic} (µgC_{mic}·g^{-1} soil) = O_2 consumption (µg O_2·g^{-1}soil·h^{-1})*28. Further details are given by Insam (1999). Arginine-ammonification was measured with the method of Alef and Kleiner (1987).

Additionally, the pH (0.01m $CaCl_2$) and the electrical conductivity of soil extracts (water-to-soil ratio 1:1) were determined.

Results

On both sampling dates, significant differences in plant cover were found (Table 2, Fig.1). In particular, Ferihum^R and Biosol^R did show good results. Generally, the addition of ACS^R significantly improved plant cover. Alginure^R and sulfur did not result in significant improvements. The same pattern was found for the vitality index (Table 2, Fig. 2). ACS^R significantly improved the vitality, and the plants on organic substrate plots looked more vital than those on the control plots.

Figure 1: Percent plant cover (a) 3 and (b) 5 months after recultivation

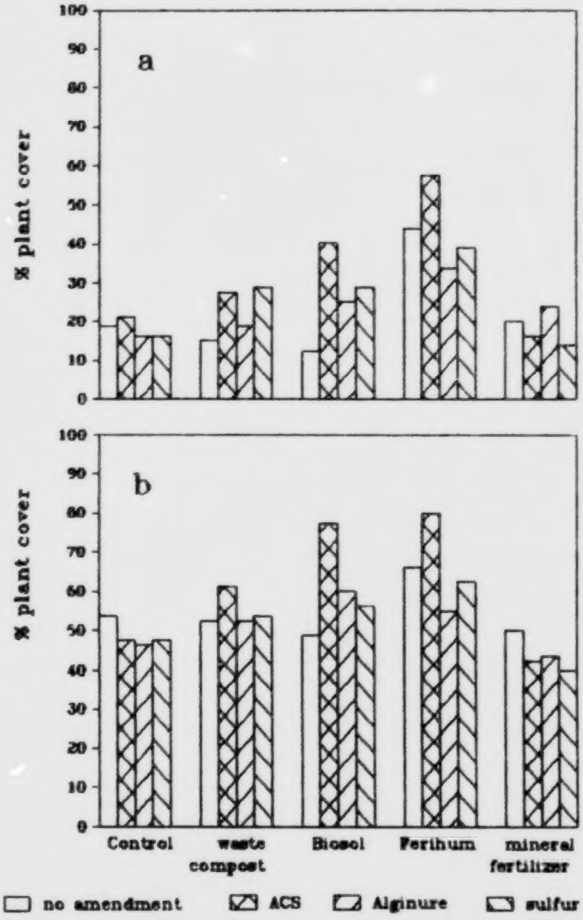


Table 2: Influence of fertilizers and soil conditioners on microbial biomass and arginine-ammonification rates - Analysis of Variance

Dependent variable	Source of variation	d.f.	F-ratio	Significance level
microbial biomass (1986)	Main effects	8	5.13	.000
	Fertilizer	5	6.53	.000
	Soil conditioner	3	2.50	.006
microbial biomass (1987)	Main effects	8	15.25	.000
	Fertilizer	5	23.43	.000
	Soil conditioner	3	1.62	.186
arginine-ammonification (1986)	Main effects	8	5.92	.000
	Fertilizer	5	6.86	.000
	Soil conditioner	3	4.25	.007
arginine-ammonification (1987)	Main effects	8	3.15	.003
	Fertilizer	5	2.86	.018
	Soil conditioner	3	4.25	.017

Figure 2: Vitality of the plants 5 months after recultivation (estimation, 5=vital, 4=vital, leaf tips chlorotic, 3=plants up to 50% yellow-brown, 2=plants over 50% yellow-brown, 1=plants dead). Data are the means of 4 estimations per plot from each of two replicates. Legend see Fig. 1.

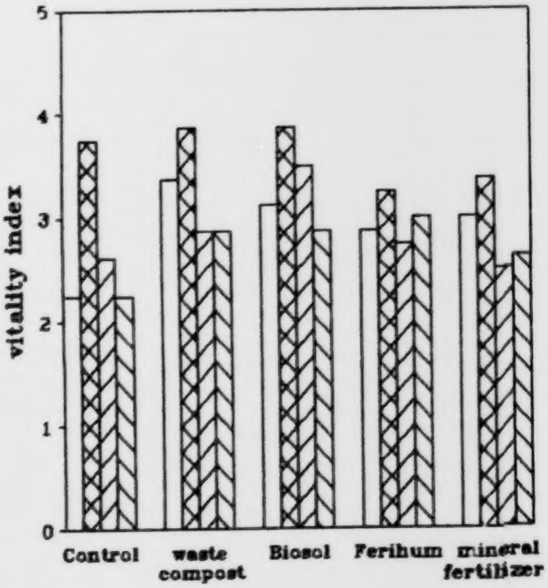
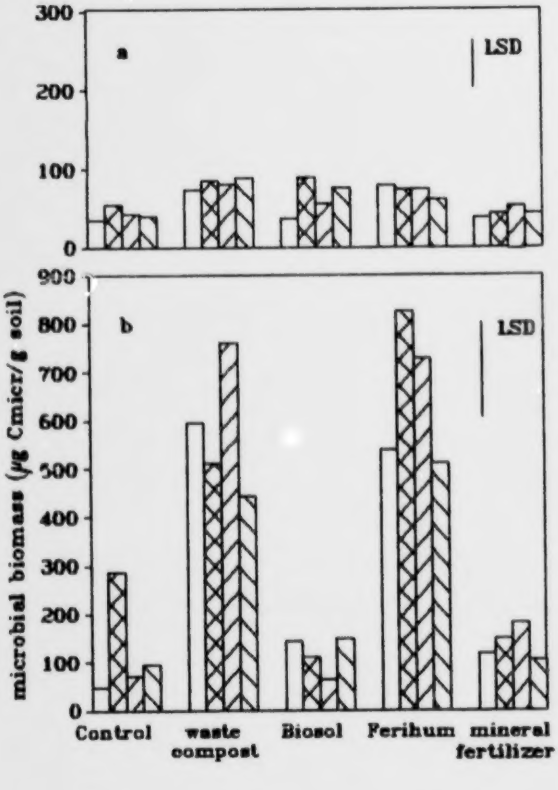


Figure 3: Effect of fertilizers and soil conditioners on soil microbial biomass. (a) First and (b) second year of trial. Legend see Fig. 1. LSD (least significant difference)



For microbial biomass, three months after initiation of the trial, significant differences were found between organically amended and control or mineral fertilizer plots (Table 2, Fig. 3). In the second year, the differences were more distinct. Then, C_{mic} was highest on the Ferihum^{R} plots. ACS^{R} significantly increased C_{mic}. Again, Alginure^{R} and sulfur did not show any statistically significant effect.

A pattern similar to that for C_{mic} was observed for arginine ammonification rates (Table 2, Fig.4).

Discussion

The results confirmed the observations by Maciak and Pronczuk (1980) who found that organic substrates increased forage yields on ash deposits, but sulfur applications did not. No relationship was found between soil pH and plant cover or vitality. The pH was determined for bulked soil samples. Thereby, microsites were disregarded. Such microsites around decomposing organic particles might be areas of intensive root growth.

The positive effects of Ferihum^{R} may be attributed to an increase of soil porosity, and thereby improved root penetration and gas exchange.

With the exception of the Biosol^{R} plots, plant growth was not related to electrical conductivity (Table 3). On the Biosol plots, where plant growth was very good, the conductivity was significantly lower than on the other plots. The lowering of the osmotic potential or the immobilisation of a toxic element may have been of importance here. Hodgson and Townsend (1973) found that in ashes, boron is frequently found in toxic concentrations.

Findings by Griffiths and Jones (1965) suggest that fungal mycelium induces a microflora that is effective in bringing about aggregation. It may be that Biosol also acted in that way.

Figure 4: Effect of fertilizers and soil conditioners on arginine-ammonification rates.

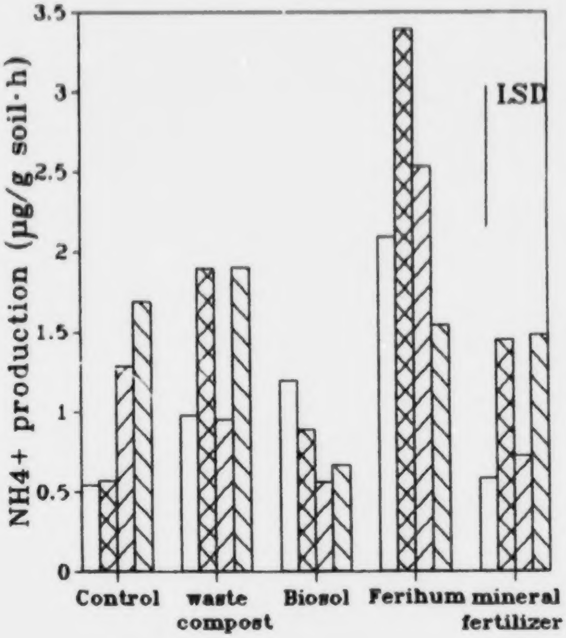


Table 3: Conductivity ($\mu S \cdot cm^{-1}$) of soil extracts. Different letters indicate significant difference ($P<0.05$).

Control	402± 65	(a)
Mineral fertilizer	457±124	(a)
Biosol^{R}	255± 39	(b)
Waste compost	535± 94	(a)
Ferihum^{R}	443±109	(a)

Organic substrates act as a carbon and nutrient source and thus have increased C_{mic}. An increase of C_{mic} by ACS^{R} may be due to a promotion of stable aggregates. Microbial activity enhances aggregation. Conversely, clay-mineral complexes are known to act conservative for C_{mic} (Tate 1987). Frequently, an increase in C_{mic} is accompanied by an increase in microbial activity. Therefore it is not surprising that the arginine ammonification rate responded similar to the different treatments as C_{mic} did.

Aim of the trial was a rapid establishment of a closed cover of vegetation on fly-ash deposits. This was accomplished best by the use of Ferihum^{R} or Biosol^{R} in combination with ACS^{R}. Ferihum^{R} and waste compost also resulted in an increase in microbial biomass and activity. Still, the long-term suitability of the reclamation measures remains to be studied.

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CORN RESPONSE TO DEEP TILLAGE ON SURFACE-MINED PRIME FARMLAND[1]

Robert E. Dunker, Ivan J. Jansen and Scott L. Vance[2]

Abstract. The effect of using a deep ripper (Kaeble-Gmeinder TLG-12) to corn grown on reconstructed mine soils was evaluated at Consolidation Coal Company's Norris Mine in west central Illinois during the 1985-86 time period. Two mine soils, one being 45 cm of topsoil replaced over graded wheel spoil and the other being wheel spoil only, were evaluated with and without the TLG-12 treatment. A nearby tract of Sable soil (Typic Haplaquoll) was used as an unmined comparison. The use of the TLG-12 which has an effective depth of approximately 75 cm was successful in significantly lowering penetrometer resistance in the 23-45 cm and 45-69 cm sample segments as compared to the unripped treatments in both mine soils. Corn yield response to the TLG-12 was significant in both 1985 and 1986, although the magnitude of response was greater in 1985, a year of higher climatic stress. Significant differences for pollination dates, % barren stalks, shelling %, and soil moisture tension levels at certain depths were observed between the ripped and unripped treatments. Corn yields averaged over the two year period for both the topsoil and wheel spoil treatment with TLG-12 were comparable to yields produced on the unmined Sable soil, while the two year non-ripped mine soils were not. No yield response to topsoil replacement occurred for either tillage treatment in either 1985 or 1986. Corn yields were significantly correlated with soil strength levels at the 23-69 segment depths.

Introduction

Soil compaction has been identified as one of the chief limiting factors in achieving post mine productivity for mine soils in Illinois. The degree and depth of compaction in mine soils varies with the reclamation practice used in reconstruction (Vance et al. 1987). McSweeney and Jansen (1984) found that mine soils constructed with a bucket wheel excavator-conveyor-spreader system resulted in a desirable fritted structure which is fairly loose and contains a network of voids favorable for water movement and root growth. Excellent corn and soybean yields have been achieved on these low strength soils in high stress as well as low stress years (McSweeney et al. 1987). Mine soils constructed with rubber tired scrapers and requiring extensive grading yielded poorly in low to moderate stress years, even though the rooting medium materials of the two methods were similar. Root penetration into the scraper placed materials was extensively horizontal instead of the normal vertical direction.

Soil strength and bulk density of graded wheel spoil from a cross pit bucket wheel excavator has been found to be at a level between those of the conveyor-spreader system and a scraper haul system (Thompson et al. 1987; Vance et al. 1987). Cross pit wheels were used extensively in the Illinois coal belt, and while they handle rooting materials more gently than a scraper system, the common practice has been to use scrapers to replace topsoil over the graded wheel spoil. Compaction created during topsoil replacement by scrapers has resulted in lower yields and increased sensitivity of row crops to weather stress (Dunker et al. 1982). The objective of this study was to evaluate corn response on wheel spoil mine soils with and without deep tillage and the effects of replacing topsoil with scrapers.

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[2] Robert E. Dunker is an Agronomist, Ivan J. Jansen is Professor of Pedology, and Scott L. Vance is a Physical Science Staff Asst, Dept. of Agronomy, University of Illinois, Urbana, IL. 61801.

Study Area and Methods

The experiment was conducted at the Consolidation Coal Company's Norris Mine located in Fulton County in west-central Illinois. The plot area was constructed in the fall of 1978 under favorable moisture conditions and maintained in forage-legumes until 1983 when corn was planted in a preliminary study. The predominate pre-mine soils of this area are in the Sable-Ipava soil association (Aquolls and Udolls), which are highly productive, dark colored soils developed in deep loess under prairie vegetation. They are characterized by having thick A horizons relatively high in organic matter, a desirable medium textured B horizon, and an underlying C horizon favorable for plant growth (Fehrenbacher et al. 1977). In the surface mining operation, the topsoil (A horizon) was segregated from the remaining profile by scrapers for later replacement after final grading. A bucket wheel excavator removed the remaining unconsolidated material and transported it across the pit. The graded resultant material is referred to as wheel spoil.

Two constructed soils, one with 45 cm of topsoil replaced by scrapers over wheel spoil and one soil consisting of graded wheel spoil only were studied. Both soils are Typic Udorthents. The wheel spoil at the Norris site consists of a mixture of leached loess, calacareous loess, calcareous glacial till, and some soft shale fragments. An undisturbed tract of Sable silty clay loam located 0.4 km away was used as an unmined comparison. Table 1 shows soil test results for surface samples (20 cm depth) from these plots taken in November 1984 for the topsoil, wheel spoil and Sable soil.

In August, 1984, under dry soil moisture conditions the Kaeble-Gmeinder TLG-12 was used as a deep tillage treatment. The TLG-12, which was developed in West Germany, utilizes a shank and moving foot to cut and lift to a depth of 76 cm. Three shanks are spaced at 81 cm and operated by auxillary hydraulics. The TLG-12 was mounted on a 750 John Deere tractor and has a productivity of 1 to 1.2 acres/ hour depending on soil conditions.

Table 1. Soil test results for surface samples (20 cm depth) from Norris plots, November 1984.

Soil Trt	pH	P1	Olsen	K
		----------- kg/ha	-----------	
Wheel Spoil	7.6	30	41	205
Topsoil	5.5	46	46	378
Sable Soil	5.7	120	98	403

Corn (*Zea mays* L.) was planted on May 20 in 1985 and May 13 in 1986 at a rate of 64,220 seeds ha^{-1} with rows spaced 76 cm apart. The hybrid used was Mo17 x B73. Management practices were similar to what would be followed by a typical central Illinois farming operation. Fertilizer was applied in a dry form (268 kg N ha^{-1}; 134 kg P ha^{-1}; 134 kg K ha^{-1}) and incorporated before planting. The herbicides atrazine and metolachlor at 2.3 L ha^{-1}and 2.6 L ha^{-1}, respectively, were preplant incorporated and resulted in excellent weed control. To control rootworm (*Diabrotica* spp) the insecticides carbofuran in 1985 and chloropyrifos in 1986 were applied through the seedbox applicator.

Dates on which 50% of the plants of a plot had silked and shed pollen were recorded and converted to days from planting for each plot. Rainfall at the research plots were recorded daily to the nearest 0.25 mm. Tensiometers were installed in each soil treatment to record soil moisture tension levels at the 30, 60, 90, and 120 cm depths twice each week. At harvest, plants per plot, ear number, and ear weight were recorded. This allowed for estimates of barren stalks, ear size, and shelling percentage on a dry weight basis on each soil treatment.

Grain yield samples were hand harvested after black-layer formation indicated physiological maturity. Grain yield estimates were based on the amount of shelled grain after adjusting for variation in moisture content of grain to 155 g kg^{-1}.

Penetrometer measurements were taken with a constant rate recording penetrometer capable of recording soil resistance to penetration to a depth of 112 cm (Hooks and Jansen 1985) to evaluate the loosening effects of the deep tillage and to characterize the non-ripped mine soils. The data was collected in April of 1986 while soils were uniformly moist to minimize the effects of variable soil moisture on penetration resistance.

Because the soil treatment blocks were located on both the mine soil area and a nearby undisturbed tract the following procedure for statistical analysis was followed for agronomic comparisons: (i) Homogeneity of variances was tested for the soil treatment area. (ii) Variances were found to be homogeneous, allowing for an analysis of variance procedure to be used to test for treatment effects. (iii) The variance for the 1985 and 1986 experiments were homogeneous, allowing for a combined years analysis to be used in interpreting responses.

Results and Discussion

Yield and Agronomic Response

Corn yields were consistently higher on the TLG-12 treated plots (Table 2). The TLG-12 effect was significant (0.05 level) over the two year study where topsoil had been replaced. On the wheel spoil, two year corn yields were 684 kg ha^{-1} higher on the TLG-12 treated areas than on the untreated areas, but the effect was not significant at the 0.05 level. Corn yields from mine soils ripped with the TLG-12 were not significantly different from yields on the Sable soil over the two year period, while non-ripped mine soil yields were significantly lower than than the undisturbed site. When averaged over the two year period, no significant response to topsoil replacement occurred for either the TLG-12 ripped or non-ripped treatments.

Weather variables were distinctly different in 1985 than 1986 (Table 3). Temperatures in May, 1985 were warmer than normal promoting rapid early season growth, while cooler than normal temperatures occurred during June, July and August. Rainfall was below normal in June and most of July. Moderate rainfall (24 mm) occurred during the pollination period of 25 July to 4 August. Weather during the growing season of 1986 was characterized by above normal temperatures in May, June, and July as well as well above normal rainfall during the vegetative and reproductive stages in June and July. 1985 could be characterized as a moderate stress year, while 1986 could be characterized as one of relatively little temperature and moisture stress.

Table 2. Mean Corn yields for mined land and Sable soil treatments at Norris mine.

Soil Trt	1985	1986	Mean
		kg/ha	
TS TLG[1]	10346	11733	10968
TS CON	7370	11394	9160
SP TLG	8280	12368	10101
SP CON	8010	11175	9417
SABLE	11068	11545	11238
LSD(0.05)	2423	1098	1406

[1] Soil treatments are as follows: TS TLG, topsoil replaced and TLG deep ripped; TS CON, topsoil replaced and conventional chisel plowed; SP TLG, wheel spoil and TLG deep ripped; SP CON, wheel spoil and conventional chisel plowed; SABLE, undisturbed Sable soil.

Table 3. Precipitation and temperatures for 1985 and 1986 growing seasons at Norris Mine.

Month	Mean Temp.	Depart. of Norm	Total Precip.	Depart. of Norm
	C		cm	
		1985		
MAY	17.9	+1.5	7.9	-1.8
JUN	20.4	-1.3	3.9	-6.0
JUL	23.1	-0.8	6.3	-3.8
AUG	21.2	-1.6	14.6	+4.4
SEP	19.2	+0.9	8.7	-0.5
		1986		
MAY	17.8	+1.5	9.2	-0.5
JUN	22.8	+1.0	16.6	+6.7
JUL	25.4	+1.5	17.2	+7.1
AUG	20.9	-1.9	4.8	-5.4
SEP	21.1	+2.5	15.0	+5.8

Soil moisture tension levels were considerably higher at the 60 and 90 cm depths in 1985 as compared to 1986 (Figure 1). Soil moisture tension levels were beyond the range of tensiometers at the 30 and 60 cm depths by pollination in 1985. Significantly higher soil moisture tension levels at the 90 cm depth the week before pollination (July 24) on the non-ripped topsoil treatment compared to the non-ripped wheel spoil. These differences may have been due to increased demand for water by vegetative growth differences, low hydraulic conductivity, or a combination of both. Lah (1980) measured saturated hydraulic conductivity on soil cores from adjacent plots to be 28.3 cm d^{-1} for the topsoil material and 12.8 cm d^{-1} for the wheel spoil. Very low conductivity values of 7.6 cm d^{-1} were measured from the wheel spoil interface with the topsoil. Plant heights for the topsoil were significantly higher for the topsoil (210 cm) as compared to the wheel spoil (197 cm) indicating a greater demand for water for the topsoil treatment. The TLG-12 treatment had significantly higher soil moisture tension at the 90 cm depth compared to the non-ripped wheel spoil which may indicate deeper rooting.

Measurement of other agronomic variables resulted in significant differences in % barren stalks and pollination date between soil treatments (Table 4). Topsoil replaced plots had a significantly higher rate of barren plants in 1985, a year of higher weather stress, as compared to the wheel spoil only treatment. In earlier studies, Dunker and Jansen (1987) have reported significant negative response to topsoil replaced by scrapers in years of moisture and temperature stress. In 1986, mine soils with the TLG-12 had a higher ratio of ears to plant number. Those plots with deep tillage produced multiple ears while the non-ripped plots had a 3-4 % rate of barren stalks. Plant population at harvest was not significantly different for the topsoil and Sable soil, but both had significantly higher populations than the wheel spoil, indicating a lower seed germination rate for this treatment.

Table 4. Percentage of barren plants and number of days to 50% pollen shed.

Soil Trt	1985	1986	Mean
	------	% barren plants	------
TS TLG	18.5	-1.9	9.4
TS CON	23.8	3.1	14.6
SP TLG	4.1	-11.8	-2.9
SP CON	0.2	4.2	2.0
SABLE	10.5	1.1	6.3
LSD(0.05)	11.7	15.4	9.0
	------	pollination, days	------
TS TLG	71.6	74.7	73.1
TS CON	72.8	78.0	75.4
SP TLG	72.8	80.5	76.6
SP CON	74.4	83.2	78.8
SABLE	70.8	75.0	72.0
LSD(0.05)	1.1	1.6	0.9

Two year average days after planting to 50 % pollen shed were significantly different for all soil treatments. Both topsoil replacement and tillage affected anthesis date. Topsoil replaced plots pollinated earlier than those plots without topsoil. Deep tillage also significantly reduced the number of days to pollen shed. These differences are believed to be due to reduced plant stress factors during the vegetative growth period. Seed emergence on the wheel spoil treatment was also generally 1 d later than on the topsoil or Sable. Early season vegetative growth was visibly greater on the topsoil and Sable. Within mine soils, those plots with the TLG-12 treatment also exhibited more vigorous vegetative growth.

Soil Strength

Results from the use of the cone penetrometer show that the TLG-12 was successful in significantly lowering soil strength to a depth of 69 cm (Table 5). Full profile graphics to the 112 cm depth are presented in Figure 2. The penetrometer resistance curve for the non-ripped (No TLG) topsoil/ wheel spoil treatment shows the deleterious effects of replacing topsoil with scrapers. The highest soil strength occurs in the zone directly below the topsoil. The TLG-12 was very effective in alleviating compaction in this zone. Correlation

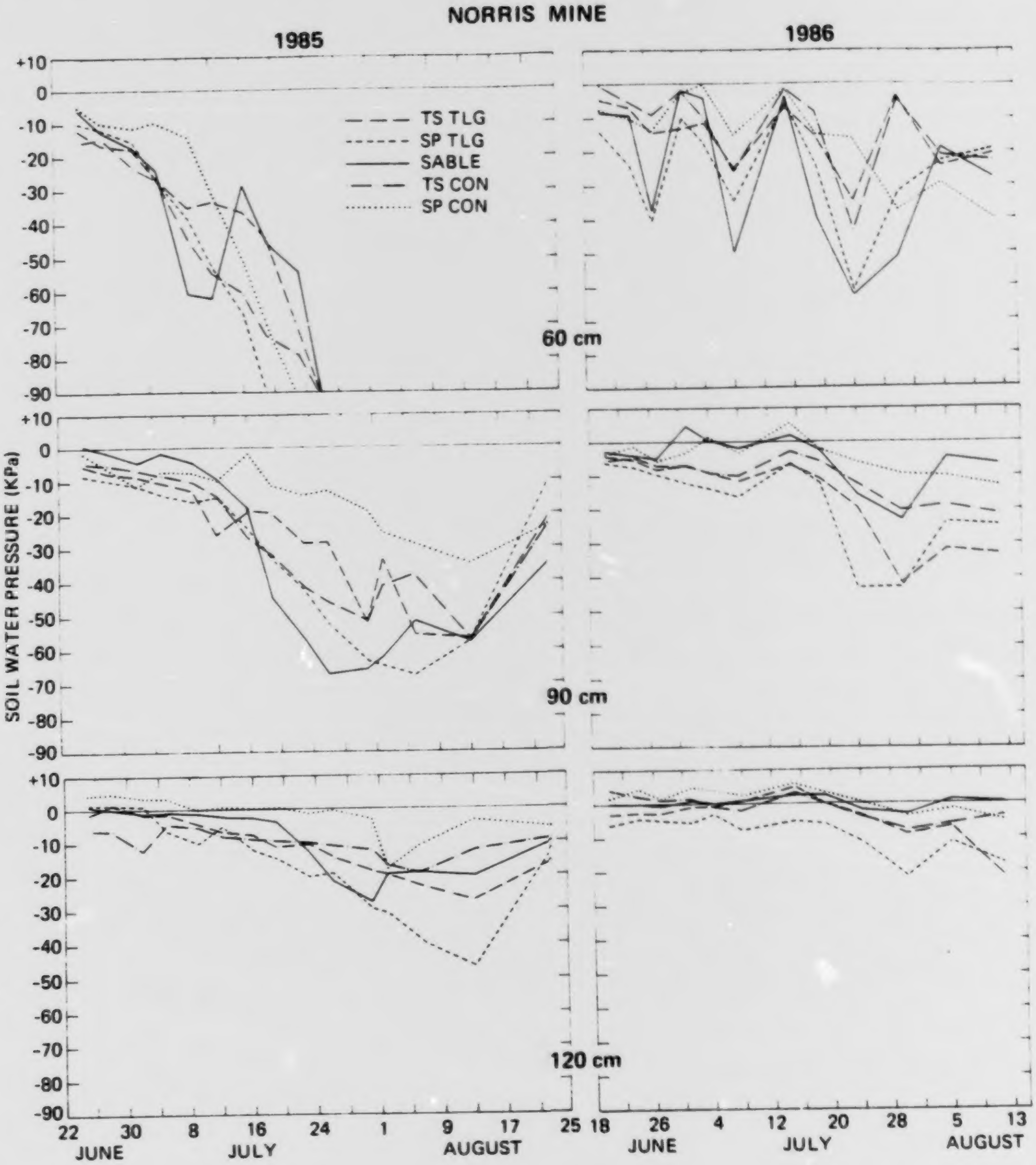

Figure 1. Soil moisture tension curves for 1985 and 1986 growing seasons at Norris Mine.

between mean corn yields for mine soil treatments and mean penetrometer resistance show that soil strength was significantly correlated with yield in the 23-45 cm segment depth at the 0.05 level and in the 45-69 cm segment depth at the 0.10 level of significance (Table 6). Corn yields were significantly correlated with the average soil strength across the 23-69 cm depth.

Table 5. Penetrometer resistance for mined land treatments at Norris Mine, April, 1986.

	Segment Depth, cm			
Soil Trt	23-45	45-69	69-91	91-112
	-------resistance, KPa-------			
TS TLG	799	715	3003	2552
TS CON	1920	3182	2926	2339
SP TLG	1050	1120	1925	2123
SP CON	1871	1966	2363	2461
LSD(0.05)	449	674	1023	1000

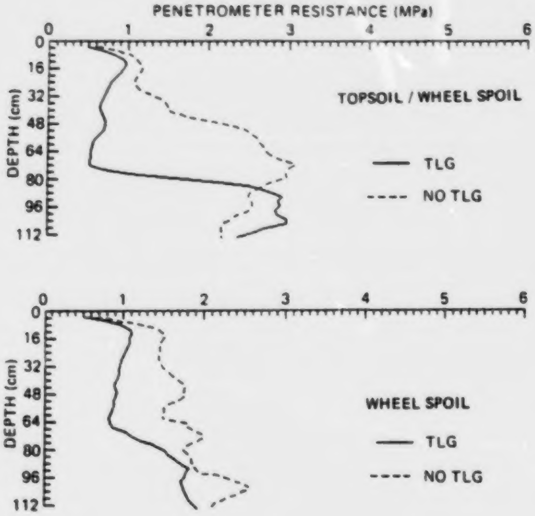

Figure 2. Penetrometer resistance curves for mined land treatments at Norris Mine, April, 1986.

Table 6. Correlations between mean treatment corn yields and mean penetrometer resistance for mine soils.

Segment (depth)	R (N=4)
2 (23-45 cm)	-0.9571 *
3 (45-69 cm)	-0.9036 +
4 (69-91 cm)	0.1424
5 (91-112 cm)	0.2770
Ave 2-3 (23-69 cm)	-0.9537 *

*, Statistically significant at the 0.05 level.
+, Statistically significant at the 0.10 level.

Conclusions

The data analyzed in this study support the following general conclusions: (i) Deep tillage to 76 cm significantly increased corn yields, with and without topsoil replaced; (ii) Soil strength as measured by a recording cone penetrometer was reduced to about the 80 cm depth by the deep tillage treatment; (iii) The deep tillage treatment consistantly advanced the corn pollination date relative to that on untreated plots; (iv) Corn yields on TLG-12 treated mine soils were similar to those on undisturbed Sable soils, whereas yields on untreated mine soils were significantly lower.

Acknowledgment

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BATTLE RIVER SOIL RECONSTRUCTION PROJECT: FIVE YEAR RESULTS OF THE TORLEA SOIL EXPERIMENT*

by

L.A. Leskiw**

Abstract. The Battle River Soil Reconstruction Project (BRSRP), featuring four experiments, was intensively monitored for five years, 1982-86. Goals were to determine the most effective methods of reclaiming mined lands using different depths and qualities of soil materials. This paper focuses on the Torlea Soil Experiment which was designed to asses the following methods of ameliorating sodicity: (1) removal of the sodic B horizon; (2) mixing the sodic B with calcium enriched C horizon; (3) applying gypsum; and (4) applying calcium rich bottom ash. With respect to crop yields there was no growth without topsoil or subsoil over spoil; poor growth with topsoil over spoil; and good growth with topsoil over subsoil over spoil. Subsoil horizon mixes and variations in depths did not result in statistically significant yield differences; however, deeper subsoils tended to yield better. Amendments proved to be very beneficial: ash outyielded gypsum and control plots. Gypsum treated plots were almost significantly higher yielding than control plots. Yields declined over time likely due to aging forage stands and to differences in rainfall. Soil quality expressed by salinity and sodicity more or less parallels yields in that better yields match better soil quality. Spoil alone is unsuitable for crop growth. Topsoil over spoil is better but salinity and sodicity levels in the topsoil remain moderate and high, respectively. Topsoils and upper subsoils have improved since construction and lower subsoils have degraded indicating leaching in the upper profile and salt accumulation at depth. These changes were more pronounced during the first couple years than later, indicating that conditions may be stabilizing, at least during current drier than normal weather. Addition of bottom ash to topsoil has been very beneficial in improving soil quality.

Additional Key Words: land reclamation; solonetzic soils; saline-sodic mine soils; amendments; reclaimed land yields.

Introduction

The Battle River Soil Reconstruction Project (BRSRP) involved establishment, soil and crop management, and research monitoring of four experiments designed to assess methods of reconstructing soil profiles following surface mining of coal in order to ameliorate the problems caused by the saline and sodic nature of the subsoils and bedrock.

The four experiments assess soil reconstruction methods in terms of soil materials, amendments and crops, as follows:

1. Subsoil Depth
   - varying subsoil depths, (ranging from 25 to 350 cm);
   - productivity of forage and cereal.
2. Torlea Soil
   - separating and mixing subsoil horizons, including different thicknesses;
   - use of gypsum and bottom ash as a surface amendment;
   - use of bottom ash as a capillary barrier;
   - productivity of forage crops.
3. Bottom Ash
   - the use of bottom ash and gypsum as a barrier to salt movement;
   - productivity of forage and cereal.

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4. Slope Drainage - manipulating the slope and aspect of reclaimed land;
   - upper, middle and lower slope positions;
   - productivity of forage.

This article presents the main findings of the Torlea Soil Experiment.

Background

Sodic mine spoil presents major technical problems in reclamation of surface mined lands in east-central Alberta. Adverse chemical and physical properties, and limited depths of reclamation materials are further complicated by climatic and hydrogeologic conditions that result in water movement and salt migration. Restoring and sustaining land capability and productivity to pre-mined levels in this dynamic environment is complex and challenging.

The most popular method for ameliorating problems caused by sodic mine spoils involves the placement of good quality topsoil, subsoil, or both, above the mine spoil to provide a root zone with favorable chemical and physical properties. Benefits of topsoil placement over spoil were well documented prior to the establishment of the BRSRP (U.S.D.A. 1977; Dollhopf et al. 1977; Grandt 1978; Nielsen and Miller 1980; Sandoval et al. 1973).

Soil depth required for adequate reclamation depends on environmental factors, intended land use and the nature of the spoil and soil materials. Soil thickness requirements for saline and sodic spoils may need to be greater than for other spoils to allow for upward salt migration, settling and subsidence, surface erosion, uneven spreading of soil material and internal drainage restrictions (Power et al. 1978). Numerous studies in the United States conducted under conditions that are considered to be similar to those at the BRSRP site revealed that optimum crop yields were obtained at total soil depths (topsoil and subsoil) ranging from about 60 cm to 120 cm (Barth and Marten 1984; Doll et al. 1984; Hargis and Redente 1984; Merrill et al. 1985; Power et al. 1981; Schuman and Power 1981).

Solonetzic soils are common in the coal fields of the Alberta plains where the bedrock of the coal bearing formations occurs close to the surface. Reclamation of lands with extensive areas of Solonetzic soils is difficult, because these soils often have very thin A horizons making salvage of suitable quantities of topsoil a problem. Furthermore, the subsoils are often shallow and have undesirable characteristics resulting from the accumulation of clay and sodium in the Bnt horizon. Additional management must be employed to improve subsoil quality. During stripping of soil materials prior to mining, the sodium enriched B horizon can be mixed with the calcium enriched upper C horizon for replacement over the spoil during reclamation.

Various chemical amendments containing calcium can be applied to remove the sodium from the soil colloids and improve the soil's physical characteristics. Gypsum has been applied with varying degrees of success to sodic strip-mined spoils. Dollhopf and DePuit (1981) found no significant effects of incorporated gypsum after 3 years of monitoring reclaimed mine spoil in Montana. Merrill et al. (1983), reported that, at four locations studied in North Dakota, gypsum incorporation increased average yields by 19% on topsoiled, highly sodic spoil. Furthermore soil water depletions and recharges were significantly higher, and the sodicity of highly sodic topsoiled spoils was decreased by up to 25%. In Alberta, gypsum was applied as an amendment to trial plots of the Camrose Ryley Project (Transalta Utilities Corp. and Fording Coal Ltd. 1987). After 10 years, topsoil salinity had increased, sodicity decreased, and average crop yields were not affected.

Ash from the coal burning thermal power stations in Alberta was considered to have potential for use as a soil amendment on sodic soils (Lutwick et al. 1981). Shaneman and Logan (1978) determined that a 15 cm layer of bottom ash contains an exchangeable calcium content roughly equivalent to 20 t/ha. The application of bottom ash over the surface of reclaimed lands increases the water holding capacity and can result in a better medium for crop growth than sodic spoil. On Bottom Ash Trial Plots, set up adjacent to the BRSRP site, ash was applied at thicknesses of 10, 20 and 30 cm and was incorporated using a disc, chisel plow or Kellough Subsoiler, or left as a blanket on the surface of the spoil (Fullerton 1987). The 30 cm rate was the most effective in promoting growth. Forage yields were higher than those reported for local farms. Eventhough ash appeared to stabilize over time, trafficability remained a problem on the 30 cm plots.

Buried bottom ash between spoil and subsoil was considered to be a useful barrier to sodium movement in that the coarse, sand-like ash would act as a capillary barrier. Its high calcium content could provide a potential buffer against sodium movement

(Parker 1981). Redente et al. (1982) working in northwestern Colorado, tested the use of gravel and cobble as a capillary barrier between a good quality topsoil and retorted oil shale having EC of 7 mS/cm and SAR of 14. The capillary barrier enabled topsoil depths to be reduced from 90 to 60 cm without a reduction of forage growth. However, the filling of capillary pores with topsoil particles was observed after 3 years and could effectively reduce the long term benefits of the capillary barrier.

Leaching of surface materials by both saturated and unsaturated percolation into and through a soil can occur. Where rainfall is sufficient, saturated flow through the soil will occur, with the wetting front proceeding at a uniform rate through the soil, provided materials are uniform. Where surface fissures and cracks are common, unsaturated flow down them can occur. Halvorson (1985) sampled seventy sites in North Dakota, reclaimed for more than 10 years, and found increases in sodium to an average depth of 38 cm below the soil-spoil interface indicating that Na had been leached out of the upper part of the profile. Richardson and Farmer (1982) found that SAR values had decreased, from 12 to below 3, in surface materials of sites in southeastern Montana reclaimed for 5 to 7 years.

The migration of salts from the sodic mine spoil into the soil materials was a major concern of reclamation in the Great Plains Region at the time the BRSRP was established. Several mechanisms are likely responsible for this phenomenon including capillarity, diffusion and convection. In central Alberta, Moran et al. (1987) found that within reconstructed soils where the water table occurred within 1.0 m of the soil surface, soils could be expected to become saline and sodic through capillary rise of water and salts: where water tables were deeper, downward leaching of salts predominated. Diffusion and convection as mechanisms of upward salt movement in reclaimed soils were studied by Merrill et al. (1983) in laboratory column studies and results were then applied to field situations. It was concluded that significant sodium accumulations did occur by diffusion when a sufficiently large chemical gradient between soil materials and spoil existed. A very low hydraulic conductivity of materials was also necessary to prevent removal of accumulated salt by leaching. It was considered unlikely, however, that Na could be carried higher than 10 to 15 cm upward into non-sodic materials. Upward salt migration to similar heights has been reported in a number of studies on the Northern Great Plains (Barth 1983, Barth and Martin 1984, Merrill et al. 1980).

Materials and Methods

The study area is in east central Alberta, about 20 km north of Halkirk. It lies within the Castor Plain Physiographic District, an area of morainal veneer and blanket overlying undulating bedrock of the lower Horseshoe Canyon Formation (Pettapiece 1986). This bedrock which occurs above coal seams is saline, sodic and high in clay, and is rated "Unsuitable" for reclamation. Where residual materials are found at or near the surface, soils of the Torlea Series (Dark Brown Solodized Solonetz) occur. The Torlea experimental plots were constructed from Torlea soil materials. A soil profile description of a native Torlea Soil follows (from Wells and Nikiforuk 1988).

Horizon	Depth cm	
Ap	0 to 11	Dark brown (10YR 4/3 m); silt loam; weak, coarse cloddy and weak to moderate, fine granular; friable; abundant roots.
Bnt	11 to 28	Very dark brown (10YR 3/2 m); clay loam; weak to moderate, very coarse columnar breaking to moderate to strong; medium, angular blocky; very firm; plentiful roots.
Csa	28 to 48	Very dark gray (10 YR 3/1 m) and dark grayish brown (10YR 4/2 m); clay loam; moderate very fine to fine, angular blocky; firm; few roots.
IICsaca	48 to 55	Dark grayish brown (10YR 4/2 m); sandy clay loam; weak fine to medium pseudo platy; firm; very few roots.
IICs	55 +	Pale olive (5Y 6/3 d); common, medium, distinct (5Y 6/6 d) mottles; loam to clay loam; weak, fine to medium pseudo platy; firm; no roots.

The project area experiences a continental climate characterized by warm summers and cold winters. January is the coldest month with a mean temperature of -16 degrees C and July is the warmest month with a mean temperature of 17 degrees C. The agroclimatic class is 2AH indicating slight moisture and heat limitations (A.S.A.C. 1987). There is adequate precipitation (400 to 450 mm annually) and a long enough frost free period (averaging over 90 days) to permit the growing of all dryland crops that are typical to the prairie region of western Canada. Growing season precipitation data presented in Table 1 indicate a micro-climatic effect such that conditions at the project compound were drier than at the nearby Forestburg Plant Site during the monitoring period.

Table 1. Precipitation (mm) Forestburg Plant Site and BRSRP Compound.

	May	Jun	Jul	Aug	Sep	Sum
			mm			
20-yr Average FPS* 1967 to 1986	45	77	72	53	42	289
5-Yr Average FPS 1982 to 1986	44	72	88	55	55	314
4-Yr Average FPS 1983 to 1986	42	78	76	45	69	310
4-Yr Average BRSRP* 1983 to 1986	32	66	58	42	48	246
1983	44	133	60	19	20	276
1984	15	67	26	38	104	250
1985	57	36	50	98	17	258
1986	12	28	93	15	52	200

* FPS - Forestburg Plant Site (monitored by Environment Canada)

** BRSRP - BRSRP Compound (monitored by Alberta Research Council since 1983).

Arable soils in the region are used for dryland crop production, mainly wheat, barley and canola: non-arable lands are utilized for pasture and forage production. Forage yields specific to the BRSRP location are scarce, since most available data are reported on a Crop District, or Agro-ecologic Unit basis. A number of sites on Solonetzic soils in Flagstaff and Paintearth Counties were studied to evaluate deep plowing, ripping, and liming feasibility, from 1982 to 1986 by the Soils Branch, Alberta Agriculture. Crop yields from a number of these trials, near the BRSRP study site, and from regional records are compiled in Table 2, based on file information provided by Alberta Agriculture.

Plots were constructed and materials were initially sampled in 1980 to establish baseline chemical characteristics. Construction simulated the "take and put" technique of mine reclamation as described by Grandt (1978). First, the area of mine spoil was levelled, then plots were constructed using Manalta Coal Ltd. - Vesta Mine machinery (dozers and scrapers).

Table 2. Forage yields (kg/ha) from agricultural lands and plot studies for comparison with BRSRP yields, 1983 to 1986.

Source*	Mean	1983	1984	1985	1986
A1	1550	1682(1)**	1457(1)	1525(2)	1535(3)
A2	2477	2959(1)	1726(1)	2915(1)	2309(2)
B	3141	3254	2940	2625	3747
C	1373	1117	676	2242	1456

* A - Yields from Solonetzic Soils Studies: (A1) control plots, (A2) 3 layer plow plots, Flagstaff and Paintearth Counties, Alberta Agriculture. Yields are from strips on farm fields.

B - Agricultural Reporting Area 4 data, Alberta Agriculture. (Farmers reported yields).

C - Paintearth Mine Torlea Soil Reclamation Trials. Reference yields (reseeded natural Torlea soil).

** Number of reporting trials.

A series of plots were established consisting of seven treatments as follows:

Treatment	Thickness of Layers
1	spoil
2	20 cm topsoil/spoil
3	20 cm topsoil/20-30 cm B+C/spoil
4	20 cm topsoil/45-55 cm B+C/spoil
5	20 cm topsoil/75-90 cm C/spoil
6	20 cm topsoil/100-115 cm C/spoil
7	20 cm topsoil/45-60 cm C/20-35 cm ash/spoil

Within each treatment surface amendments of 15 cm bottom ash and 20 t/ha gypsum were each spread on each of two subplots and incorporated during cultivation, while the third subplot was a control. Plot dimensions are 4 m x 24 m and each subplot is 4 m x 8 m. Note that actual depths of soil layers varied from original design specifications hence the ranges in thicknesses of subsoils. Selected properties of materials determined from grab samples collected during construction are given in Table 3 and original soil quality is rated according to recent guidelines (Alberta Agriculture 1987). Samples were air dried and pH, EC (electrical conductivity), SAR (sodium adsorption ratio), and soluble Na, K, Ca, Mg, Cl, and SO4 were determined by saturated paste extract (McKeague 1978). The same methods were used subsequently in the annual monitoring of soils.

Table 3. Selected properties of materials from grab samples taken during construction.

Material	n	EC(mS/cm) Mean	SD*	SAR Mean	SD	SUITABILITY RATING**
Topsoil	90	2.4	1.0	13.5	1.2	U(SAR)
Subsoil	252	5.7	1.3	14.2	1.6	U(SAR)
Spoil	21	2.7	0.7	20.2	4.6	U(SAR)
Ash		1.2	0.2	24.5	3.7	-

Source: Techman Engineering Ltd. 1982, n = number of samples per reported mean.

* SD = Standard Deviation

** Alberta Soil Quality Criteria (Alberta Agriculture, 1987).

Ratings	Constraints
U - Unsuitable	SAR - High sodium adsorption ratio (sodicity)

One of the major aspects of reclamation of surface mined lands involves the use of readily available materials for soil reconstruction. Materials assessed for reclamation in this research include the following:

Topsoil: loam to clay loam textured Ah or Ap horizon material removed from the native soils before mining. It had an "Unsuitable" rating because of its excessive sodicity, based on Alberta soil quality criteria (Alberta Agriculture 1987).

Subsoil: clay loam B and C horizons plus underlying material that has chemical and physical properties suitable for sustaining vegetative growth. Subsoil materials consist of shallow till and weathered bedrock and are rated Unsuitable because of high sodicity.

Spoil: consists of clayey sodic bedrock materials of the Horseshoe Canyon Formation. It is "Unsuitable" reclamation material because it has SAR values above 20. The relatively low EC values in comparison with the SAR values is characteristic of spoil materials of the Northern Great Plains (Power et al. 1978).

Bottom Ash: the waste product of coal burned at the Battle River Thermal Power Station. It is a sandy textured, pumice-like material characterized by relatively high calcium content and potentially toxic concentrations of boron (McCoy et al. 1981).

Gypsum: was applied at 20 t/ha as a surface amendment and as a 20 to 35 cm layer below the subsoil in Treatment 7.

One neutron probe aluminum access tube was installed at the centre of each subplot to a depth 50 cm below the subsoil/spoil interface. Soil water was measured monthly, May through September, at specified depth increments with a Campbell Scientific Hydroprobe Subsurface Moisture Gauge, Model 503. Soil bulk density was measured annually with a Campbell Pacific Model 501 Nuclear Depth Probe. Both probes were calibrated annually by regression analysis of apparent readings and gravimetric measurements.

The soils within each subplot were sampled at a different point on a 1 m x 1 m grid each autumn with a 7.5 cm coring tube, at 15 cm intervals, continuing into the underlying spoil. Depths to material interfaces were noted and samples were taken above and below interfaces to preclude mixing of materials. Roots were described in the soil cores by noting depth, abundance and size in accordance with standard definitions (Agriculture Canada 1975).

An attempt to establish a forage mixture in 1981 failed so in 1982, Neepawa wheat was drill seeded as a nurse crop at a rate of 55 kg/ha and underseeded with Carlton bromegrass (*Bromus inermis*) drilled at 8 kg/ha and Rambler alfalfa (*Medicago sativa*) broadcast at 15 kg/ha. Fertilizer was broadcast each spring at recommended rates of approximately 45 kg N/ha, 45 kg P/ha, and 22 kgK/ha.

Forage yields were determined by mowing with a lawn mower and bagger 2 m x 6 m central portions of each subplot in mid to late July, 1983 to 1986. Yields were determined on a dry weight basis calculated from entire plot fresh weights measured in the field and subsamples oven dried at 30 degrees C for 48 hours.

Yield, saturation %, EC and SAR were analyzed statistically using a split-split-plot design with treatments as the main plot factor, amendment as the subplot factor and year as the sub-subplot factor. The amendment main effect was analyzed as three planned contrasts. Year main effects were decomposed into planned linear and quadratic contrasts using standard coefficients (Snedecor and Cochran 1980). Additional post hoc comparisons, including comparisons of treatment means, were conducted using Tukey's HSD at p=0.05. Data on soil moisture, density and rooting were summarized and used as an aid in interpreting soil forming processes.

Results and Discussion

Forage Yields

Forage yields were measured on first cuts taken each July, 1983 to 1986. Results are not presented for Treatment 1 which had little growth on ash amended plots and no growth on the others. Yields for Treatments 2 to 7 are given in Table 4: they were lowest for Treatment 2, highest for Treatments 3 to 6, and intermediate for Treatment 7. A pattern of gradually increasing yields corresponding to increasing subsoil thickness from 20 to 115 cm is evident, but not statistically significant. Treatment 7 with a buried ash layer between the spoil and subsoil produced inferior yields compared to subsoil alone, regardless of subsoil thickness.

Table 4. Forage yields 1983 to 1986.

Treatment	2	3	4	5	6	7
kg/ha	1872a*	3514b	3700b	3761b	3813b	3168ab

**n = 36, s.e. = 325, c.v. = 1595.

Amendment	1 (Ash)	2 (Gypsum)	3 (Control)
kg/ha	3624b	3292a	2986a

n = 72, s.e. = 113, c.v. = 330.

Year - linear and quadratic contrasts indicate a decline with time and a peak in 1984.

Year	1983	1984	1985	1986
kg/ha	3397b	3998c	3033ab	2783a

n = 54, s.e. = 138, c.v. = 520.

Year x Amendment

Year	1983	1984	1985	1986
Ash	4319cd	4174cd	2749ab	3256abc
Gypsum	3186abc	3942cd	3355abc	2685a
Control	2642a	3878bc	2994abc	2408a

n = 18, s.e. = 240, c.v. = 1166 (not within year).

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* Values followed by same letter are not statistically different.

** n = number of observations per mean; s.e. = standard error; c.v. = critical value.

Surface amendments had important effects on crop growth. The control plots yielded lowest, gypsum treated plots were intermediate and almost statistically higher than controls, and ash amended plots yielded highest.

Time also had a significant effect in that yields peaked in 1984 and declined subsequently, the latter likely due to aging stands and to intensifying spring drought. Time amendment interactions were important in that yields on ash > gypsum > control in all years except 1985. Poor yields on ash amended plots in 1985 were likely a result of serious gopher damage which occurred only on ash amended plots.

In comparing these plot yields with those of other studies and farmers reported yields in the region (Table 2) it is clear that reclamation was very successful as evidenced by much higher crop productivity on the Torlea Treatments 3 to 7.

Soil Salinity

This section addresses saturation %, EC and SAR in topsoils, upper subsoils and lower subsoils, and spoils. Statistically significant findings are given in Tables 5 and 6. Significant interactions usually between year and amendment or year and treatment also occurred and are discussed.

Topsoils: There were expected marked differences in saturation %, in that both ash and gypsum amendments reduced saturation % relative to the control. There was also a decrease with time, most pronounced in the early years. EC and SAR levels were different in response to treatment, amendment, year, and interactions of these. In summary, the following are the most important results regarding topsoil quality after five years:

Treatment: Treatment 1 (no topsoil) was unsatisfactory throughout. Treatment 2 (topsoil over spoil) was better than Treatment 1 but inferior to Treatments 3 to 7 with subsoil. As of 1986, topsoils in Treatment 2 had highest EC and SAR levels, due to upward movement of sodium from the spoil or limited leaching, or both. Treatment 6 topsoil ranked next and was higher in EC and SAR than others.

Amendment: While ash caused trafficability problems, it clearly helped to improve topsoil chemical and physical properties. In ranking amendments, ash was usually superior, such that: EC - ash < control < gypsum; and SAR - gypsum < ash < control. Gypsum was effective in reducing SAR whereas ash "diluted" the soil and effectively enhanced infiltration, leaching and thereby reduced EC.

Time: EC and SAR decreased over the five-year period, with the major declines occurring in the last couple years.

Subsoil: Upper subsoils also differed in saturation percentage, EC and SAR.

Treatment: Saturation percentage of C materials was higher than of B+C mixes.

Table 5. Topsoil salinity, 1982 to 1986.

Treatment	2	3	4	5	6	7
Sat%	81b	61a	62a	62a	70ab	65a

n = 45, s.e. = 2.92, c.v. 14.3.

Amendment - ash (63) and gypsum (65) < control (72).

Year - linear and quadratic contrasts are significant, and there are differences between years.

Year	1982	1983	1984	1985	1986
Sat %	87c	69b	62a	58a	57a

n = 54, s.e. = 1.6, c.v. = 6.2.

Treatment	2	3	4	5	6	7
EC	4.1b	2.2a	2.2a	2.5a	3.3a	2.6a

n = 45, s.e. = 0.23, c.v. = 1.2.

Amendment	Ash	Gypsum	Control
EC	1.7a	4.1c	2.7b

n = 90, s.e. = 0.12, c.v. = 0.4.

Year - the linear decrease with time is significant.

Year	1982	1983	1984	1985	1986
EC	3.4	3.5	3.0	2.3	2.0

n = 54.

Treatment	2	3	4	5	6	7
SAR	18b	6.2a	8.7a	8.4a	10a	9.3a

n = 45, s.e. = 0.94, c.v. = 4.6.

Amendment	Ash	Gypsum	Control
SAR	9.5b	7.8a	13c

n = 90, s.e. = 0.40, c.v. = 1.4.

Year - The linear and quadratic contrasts are significant.

Year	1982	1983	1984	1985	1986
SAR	13	11	13	8.9	4.4

n = 54.

Amendment: Amendments are ranked the same as in topsoils for levels of EC indicating enhanced leaching in upper subsoils likely due to superior physical properties in the topsoil. But SAR levels in upper subsoils did not differ among amendments. **Time:** Linear and quadratic contrasts are significant for saturation %, EC and SAR. Saturation % decreased with time and levelled off in the last two years; EC increased with time then appeared to be levelling off; SAR increased, peaked in 1984, and then decreased but in 1986 was still above initial levels.

Table 6. Upper subsoil salinity, 1982 to 1986.

Treatment	3	4	5	6	7
Sat %	70a	72ab	94bc	96c	101c

n = 45, s.e. = 4.8, c.v. = 23.

Year - the linear decline and quadratic contrasts are significant.

Year	1982	1983	1984	1985	1986
Sat %	110c	92b	84a	77a	79a

n = 45, s.e. = 1.8, c.v. = 7.1.

Amendment	Ash	Gypsum	Control
EC	6.0a	7.7c	6.8b

n = 75, s.e. = 0.19, c.v. = 0.7.

Year - linear and quadratic contrasts are significant.

Year	1982	1983	1984	1985	1986
EC	5.0	6.6	7.3	7.6	7.8

n = 45.

Year - the quadratic contrast is significant.

Year	1982	1983	1984	1985	1986
SAR	16	19	21	18	17

n = 45.

Caution is advised in interpreting the technical significance of these results due to effects of declining saturation % over time. When saturation % is adjusted downward to be constant, EC levels in the early years become relatively higher. The overall trend becomes gradual improvement in upper subsoil quality over five years rather than initial degradation followed by improvement as signified by results given. This occurs in spite of salts being leached from topsoils and added to the upper subsoils.

Lower subsoils changed with time such that saturation % decreased mostly in the second year; EC increased considerably from 1982 to 1984 (6 to 9) then appeared to level off; SAR increased from 17 in 1982 to 24 in 1984 and declined to 19 in 1986. Without or with adjustments to standardize saturation %, final EC and SAR values are higher than 1982 values, indicating increasing salinization of the lower subsoil. Spoils in the layer below the interface did not change significantly over time. In

1983, EC was 5.9 and SAR was 32: in 1986, EC was 6.3 and SAR was 30. Note that EC levels in 1983 exceeded values from grab samples taken during construction (Table 3). Since fewer samples were taken during construction, it cannot be ascertained whether the apparent increase is due to spatial or temporal variation.

Soil Moisture

Major factors considered in gathering and interpreting moisture data included: moisture availability to plants and depth of rooting; occurrence of saturated conditions, or perched water table; and effects of moisture on soil development. Lab analyses of disturbed samples were conducted to determine wilting point (WP) and field capacity (FC). Values for topsoil are 22% and 40%, respectively, and for subsoil they are 29% and 47%, respectively, or a volume basis. Meaningful values for spoil could not be determined due to high sodicity; however, for reference purposes the subsoil limits are used. To summarize the five year data soil moisture classes were developed indicating droughty (wilting point plus 5% moisture) and readily available (remaining available moisture) soil moisture levels for crop growth (Can-Ag Enterprises 1989).

Maximum moisture levels seldom exceeded field capacity and never approached saturation %. This indicates an absence of water tables within the monitoring depths. Driest moisture levels measured by neutron probe on Torlea topsoils and subsoils were about 10% less than the mean wilting points determined by lab measurements. The wilting point moisture content used for spoil matched the lowest readings observed. Generally, the topsoils had moisture contents within the readily available range about one-third of the time in gypsum and control subplots and two-thirds of the time in ash subplots. The ash amended topsoils appear to store more moisture, perhaps reflecting higher infiltration rates and less runoff. This could be very important in "trapping" rainfall from short, intensive summer storms. Subsoils were generally always very dry in ash subplots; moist in the upper subsoil some 10 to 15% of the time in gypsum subplots; and moist about 20% of the time in control plots. This overview of subsoil moisture reflects trends opposite to those of yields suggesting that higher moisture extraction contributes to higher yields and reduces soil moisture contents.

Bulk Density

Measurements of apparent soil density in 1983 indicated the following mean values for control subplots, in g/cm3; topsoil 1.10; upper subsoil 1.48; lower subsoil 1.45; and spoil 1.45. Soil densities on a dry weight basis were calculated by subtracting moisture content as measured by moisture probe from soil density at field moisture levels as measured by density probe. The readings must be considered as approximate in this context as they are dependent on calibrations and operating errors of two instruments. Nevertheless, the soil density values obtained are considered to be within the range for natural soils but the subsoil densities are considerably lower than those found on the other three adjacent experiments where subsoil densities averaged around 1.80 g/cm3 (Can-Ag Enterprises 1989).

Root Distribution

All topsoils in Treatments 2 to 7 contained abundant fine and very fine roots. Subsoils had plentiful roots to 35 to 60 cm below ground surface and few roots beyond to a maximum of about 130 cm. Root penetration into spoil was limited to some 15 cm. Amendment effects were clear in Treatment 1 (spoil); in that the ash amended plots had much more forage growth and more roots than gypsum and control plots. In other treatments, effects of amendments were not well defined; however, it appeared that gypsum promoted deeper rooting in Treatment 6.

Synthesis

Treatment Effects

Treatment 1, no topsoil over spoil, was totally unsatisfactory as there were complete crop failures except on the ash amended subplots which yielded very poorly. Soil properties (EC, SAR) and soil quality remained Unsuitable throughout the monitoring period. Treatment 2, 20 cm topsoil over spoil, yielded poorly compared to treatments with subsoils. Topsoil quality remained Poor due to excessive SAR. It appears that leaching of salts was either restricted or countered by upward migration of sodium salts from spoil, or both. The rooting zone was severely restricted by shallow spoil so that available water storage capacity was essentially limited to that of the topsoil. Treatments 3 to 6, topsoil over increasingly thicker subsoils (correspondingly about 25, 50, 80 and 110 cm) produced good yields, almost doubling those obtained on similar natural soils in the region. There were increasing yields with increasing subsoil thickness, however this was not statistically significant. Topsoils in Treatments 3 to 6 improved from Poor to Fair at the start to Good by 1986, resulting from downward leaching of soluble salts. All upper subsoils remained Unsuitable but those in Treatments 4 and 6 were improving in the latter years while those in Treatments 3 and 5 were degrading as measured by EC changes of about 1 unit. Treatment 3, was degrading, possibly due to shallow depth to spoil (40 to 50 cm). More time is needed to determine whether these trends will become more pronounced and statistically significant.

Treatment 7, topsoil over 50 cm subsoil over 25 cm ash over spoil, had lower yields than Treatments 3 to 6; therefore buried ash was detrimental. There was no apparent beneficial or detrimental effect on subsoil quality compared to other treatments. Lower subsoil, that is, the layer above spoil, degraded an average of about 1 unit in EC in Treatments 4 to 7. This may be due to accumulation of salts leached from above, to upward migration from spoil, or both.

Amendment Effects

Forage yields across Treatments 2 to 7 were best on ash (3620 kg/ha) amended plots, followed by gypsum (3290 kg/ha) then control (2990 kg/ha). This is about a 10% difference between each. Treatment x amendment interactions were not significant, but the relative increases in yields imply the ash or gypsum surface amendments are much more effective than 30 cm increments of subsoil beyond a 50 cm thickness. The benefits of ash, however, are partly negated by poor trafficability and the duration of benefits or problems under repeated cultivation is not known.

Amendment effects were also important as EC and SAR levels in topsoils and upper subsoils clearly show that the ash amendment is superior. Gypsum is ranked intermediate: EC was highest in topsoils and upper subsoils, but SAR was lowest in the topsoils. Control plots had intermediate EC levels but highest SAR in topsoils and intermediate EC levels in upper subsoils. Over time, as topsoils improved, differences in chemistry between amendments and the control were decreasing.

In upper subsoils, there were very minor differences initially, grading to most pronounced differences and increasing levels in 1984, then improvement and declining differences in the last couple years. Therefore, it appears that Ash followed by Gypsum helped to hasten soil improvement in the upper profile. More time is needed to establish the longer term equilibrium.

Concerns

The results of this experiment are similar to those reported in the literature considering response to soil depth and amendments. However, the high yields compared to farmers yields and to those on the other three experiments at the BRSRP compound are puzzling. While initial construction design specified 10 cm of topsoil to match native soils, the final depths were about 20 cm. Also, bulk densities of subsoils in this experiment are in the order of 0.20 to 0.30 g/cm3 less than in the other BRSRP experiments. Lower densities should increase water availability in the root zone. The combination of thicker topsoils and lower soil densities no doubt contributed to the excellent yields and may have masked the importance of other characteristics including subsoil depth and horizon mixes.

At this time a salt accumulation layer is developing in the lower subsoil regardless of depth to spoil. If salt concentrations in this layer continue to increase, the salt levels could restrict the rooting zone making it somewhat shallower. Periodic monitoring in the future should establish whether this occurs.

Summary and Conclusions

Reconstructed soils consisting of 20 cm of topsoil over increasing thicknesses, from about 50 to 110 cm, of saline-sodic subsoil over sodic spoil were found to out-yield natural soils comparable to those from which the construction materials originated. However, caution is advised in extrapolating the results in that the reclaimed soils had thicker topsoils (20 cm) than the native soils (10 cm).

Topsoil quality improved significantly over time as salts were leached downward. Upper subsoils seemed to be improving in some treatments and degrading in others but more time is needed to determine whether current trends become statistically significant. Lower subsoils degraded over the five year period, regardless of treatment, indicating accumulation of salts leached from the upper profile.

Additions of ash and gypsum as surface amendments enhanced yields and improvement of quality of upper soil layers. The better yields are likely attributable to increased moisture availability resulting from the effects of the amendments.

Acknowledgements

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SALT TAILINGS-THE ULTIMATE SALINE RECLAMATION CHALLENGE[1]

by

R. T. Hart[2]

Abstract: Potassium, one of the three essential nutrients necessary for plant growth is supplied in fertilizer form by the beneficiation of various potassium rich evaporates referred to as potash. Canada, mainly Saskatchewan produces about 20% of world production and has almost 70% of the world's conventionally mined ore. Of the 71 operations throughout the world, most rely on standard shaft mining techniques and dispose of their tailings on surface. Tailings which comprise at least 60% of even the best grade ore as found in Saskatchewan, are predominantly NaCl. Contamination of surface and ground water by brine originating from surface storage of waste process brine and precipitation on the salt tails is the main environmental concern facing the industry. The industry has met with some success in containing the brine and limiting environmental impact using both active and passive containment measures. Little consideration has been given to the abandonment and decommissioning of potash tails piles. If mining techniques remain the same, by the time Saskatchewan's reserves have been depleted using conventional underground techniques, the 10 existing tailings piles comprising 250 M tonnes of salt will increase to 200, containing 30 000 Mt and covering 1600 km^2. The impact on Saskatchewan's ground and surface water resource will be disastrous unless alternative methods of tailings disposal can be developed or the tailings can be isolated from the environment. As long as a mine is operational, supporting active brine containment measures, ground water contamination can likely be kept to an acceptable level. Decommissioning will be site specific and likely involve a number of options at any one site. Surface storage of salt wastes, especially in a rechange position will no longer be acceptable in Saskatchewan due to the potential for extensive ground and surface water contamination. Research is required to determine the capacity of both surficial and deep aquifers to receive brine; long term changes in the rate of brine release from salt tailings; the feasibility of returning salt tailings underground; and reclamation of severely salt contaminated sites using soil covers and vegetation.

Additional Key Words: salt tailings, potash, reclamation, containment, brine disposal, aquifers, deep well injection

Introduction

Research into reclamation and environmental concerns regarding potash waste is in its infancy. Even though potassium (K) is one of the three major plant nutrients, its widespread use as a fertilizer did not develop as quickly as it did for nitrogen and phosphorous. Potassium is a relatively common element accounting for about 2.5% of the earth's crust, and until recently has been available to crops in sufficient quantities. The increase in demand for potash as a source of potassium fertilizer has resulted in expansion of mining facilities throughout the world, notably in Saskatchewan. Due to its brief history, there is little understanding and until recently, little awareness of the short and long term environmental implications of the extraction and processing of potash ore.

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History

It was not until 1861 that the first potash mine was completed in the Strassfurt region of Germany. Development was restricted to Germany, until 1914 when France became involved following the discovered the Alsatian deposits.

It took the outbreak of World War 1 to initiate a potash industry in North America. Unlike the situation in Germany and France, the initial potash processing was not associated with underground extraction but rather with the use of naturally occurring surface evaporates at Searles Lake, California, Utah's Great Salt Lake and in Northern Nebraska. Within 3 years production peaked to 70 kt/a KCl at 65 plants but rapidly declined to a handful of producers, once the European sources were again accessible. It was not until 1931 that North America became a significant supplier of potassium, eventually opening seven mines near Carlesbad New Mexico. During the same period, European reserves were exploited in Poland, Spain and Russia, and at the Dead Sea in Palestine. Following World War 11 the Soviet Union annexed Poland's East Galatian mines, and Germany's production was split 60-40 between the German Democratic Republic (GDR) and the German Federal Republic (GFR).

Despite the initial discovery of potash in Canada during oil exploration in 1943, it was not until 1952 that the first attempt to exploit the vast Saskatchewan reserves was undertaken (Fig 1, 2). Exploitation of the ore body, that would eventually account for 70% of the world's conventually recoverable reserves, and 20% of it annual production (Energy, Mines and Resources 1982, Sheldrick and Stier 1978) did not get underway due to shaft flooding until 1962. By 1969 Saskatchewan's 10 mines were operating with a total capacity exceeding 10 M t/a.

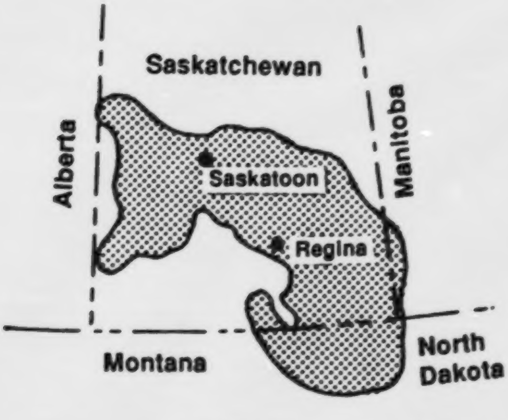

Figure 1: Location of Saskatchewan's potash ore body.

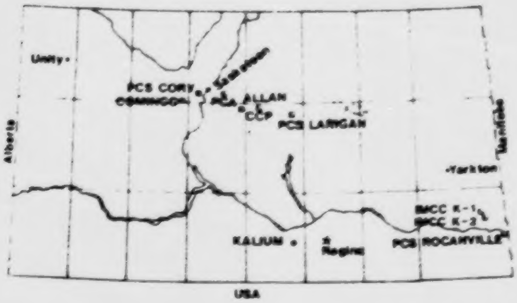

Figure 2. Location of Saskatchewan's 10 potash mines and refineries.

During the late 1950's and the early 1960's China began processing surface brine and Sicily began to mine its underground reserves. About the same time as Canada entered into potash production, Spain began exploiting its Navarra deposit and the Soviets opened their first mine in Byelorussia. In 1964 the United States commissioned their newest potash operation at Cane Creek, Utah. In the latter part of the 1960's the Congo Basin reserves in West Africa were opened, only to be flooded and closed in 1977.

Most recent activity has been confined to Great Britian (1973) , eastern Canada (1983 and 1985, New Brunswick), Brazil (1985), and Australia (1974-1976), Israel and Jordan (mid 1980s). The latter three are surface operations (The British Sulfur Corporation 1985).

Ore Bodies, Recovery and Processing

The vast majority of the world's 71 potash mining operations exploit subsurface evaporites (Sheldrick and Stier 1978), deposited as long ago as 400 million years ago, as in the case of the Saskatchewan and Byelorussia. Deposits range from 100 m below surface to in excess of 1200 m, with most between 500 m and 1000 m. Two operations are open pit and seven exploit surface deposits. The remainder are conventional subsurface mines with the exception of three which extract feed by solution mining.

Although there are a number of potash ore types, the most common and richest in K is sylvinite - a combination of KCl and sodium chloride (NaCl). Separation of the KCl in North American is by flotation with dissolution and recrystallization to enhance recovery. Flotation separates KCl from the salt wastes through attachment of air bubbles to the KCl particles. Dissolution and recrystallization exploits differences in solubility between KCl and NaCl. Dissolution - recrystallization is used alone in several plants in France, Germany and in older operations in eastern Europe and the Russia. Only one refinery, located in West Germany utilizes electrostatic separation to remove NaCl prior to flotation.

Waste Generation and Handling

Flotation and recrystallization consume large quantities of water. In Saskatchewan about 1 m^3 H_2O is required for every tonne of KCl produced (Fig 3). Brine migration from the extensive waste management sites is the most significant environmental concern facing the potash industry. Air emission impacts on soil and vegetation are relatively minor , due to effective controls. (Hart 1983, Rennie 1983).

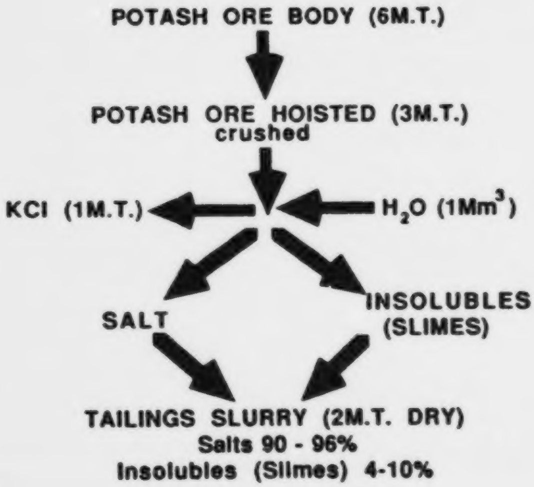

Figure 3: Process flow chart showing water consumption and product to waste ratio.

Production of solid waste is significant even in the richest ore bodies. In Saskatchewan, the waste : product ratio is about 2:1 (Fig. 3). NaCl is the major waste component , comprising more than 90% of the total waste, with KCl (<10%), and insolubles (2-9%) make up the remainder. The insoluble fraction, also referred to as slimes and insols is mainly clay and dolomite, and small quantities of quartz, potassium feldspar, microcline and anhydrite (SRC 1982).

In most cases solid wastes are disposed of on surface. Under certain geological conditions they are returned underground as is done in the Hanover area of Germany, in New Brunswick and in some mines in the U. S. S. R.. Although no producer in Saskatchewan disposes of waste in this manner, the Potash Corporation of Saskatchewan (PCS) (Taylor and Butcher 1983) has considered using solid waste to support the mine back to increase extraction efficiency and reduce surface waste storage. International Minerals and Chemical Corp. (IMC), also located in the southeastern Saskatchewan, is presently investigating the feasibility of returning solid waste underground in the form of a slurry.

Dissolved salt waste and waste brine are in some situations injected into saline aquifers. In West Germany over one-third of the 20 Mt of salt waste generated per year is injected into saline aquifers above the mining formations (Scroth 1977, 1973) while in Saskatchewan 10 to 15% of the salt waste is disposed of in aquifers below the ore body. In Germany some of the brine (1%) appears to be resurfacing. Saskatchewan's receiving formations which are much deeper (>1 000 m) discharge in Manitoba and N. Dakota (Reeves 1989). The impact of a possible increase in the discharge rate, due to injection has not been studied.

In Saskatchewan, even though the injection well capacity is sufficient to dispose of all process brine, most is still stored on the surface in large tailings ponds (Fig. 4) for slurrying of wastes. Additional brine is generated by precipitation falling on the tails pile and the brine ponds. Annual precipitation (35 cm) on tailings and brine ponds which cover from 100 to over 400 ha, can produce an additional 350 000 to 1 400 000 m^3 of saturated brine. Loss by evaporation likely accounts for a large proportion of this precipitation generated brine. France and the U.S.S.R. don't utilize injection, relying on disposal into surface waters and large evaporative ponds, respectively (Chomiak 1983, Scroth 1977, 1973).

Instead of utilizing deep well injection, the East German and French producers dissolve tailings and pump the salt waste into rivers. This practice has resulted in elevating chloride levels in some parts of the Rhine above limit set for human consumption (Chomiak 1983). Three mines located in Brazil and Atlantic Canada and Britain use the Atlantic for disposal.

The majority of potash wastes are stored on surface in Saskatchewan. Salt wastes are pumped as a slurry (25 - 30% solids) to large tails piles ranging in area from 50 to 200 ha, and 20 to 60 m in height. Due to the competence of salt tailings, pile slopes usually stand at 30° to 35°, with the exception of the long, gentle (2°) decant slope which serves to settle the solids before the waste brine reaches the brine ponds. The height of the piles does not seem limited by the tailings strength but rather by that of the soils underlying the tailing. Failure of foundation soils is possible due to build-up of pore pressure caused by rapid loading (Johnson 1984).

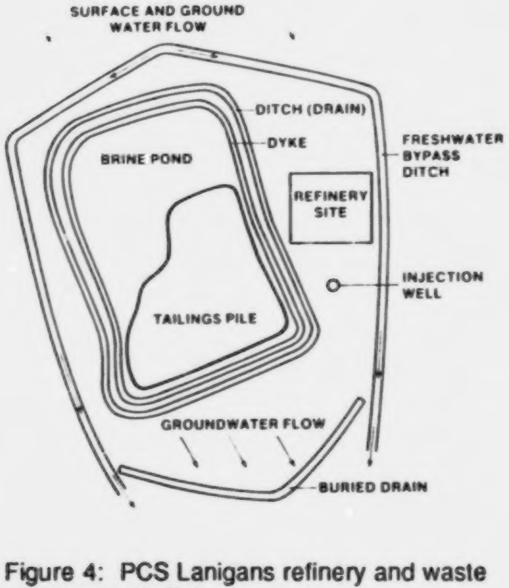

Figure 4: PCS Lanigans refinery and waste management site.

Tailings Hydrology

An understanding of the hydrology of potash tailings is required to determine the rate of brine generation and location of discharge, which is essential in designing a containment and decommissioning strategy. The only general model proposed for potash tailings was proposed for tailings in the Alsace region of France. Taleb and Valentin (1975) indicated that nearly one-sixth of the precipitation falling on potash tailings runs off the pile, while one-third infiltrates the surface and percolates through the pile to discharge in the groundwater. The remainder evaporates. In Germany, Scroth (1977) reported a similar evaporative component.

The European model does not at first appear to be applicable to the Saskatchewan situation where runoff and evaporation from the pile seems to be insignificant, at least for small events (Shook and Reid 1986). The differences may be explained by the nature of the pile surface. In Europe and the U.S.S.R. the tailings are frequently much higher in insoluble materials, which have been reported to form a crust of low permeability within a few years of abandonment (Heinz and Fiedler 1979, Bogomolov et al. 1977, Golovin 1976). Saskatchewan tailings are not only much lower in insoluble material but have also had little opportunity to weather (Hart 1988).

An unknown proportion of the total recipitation and process brine discharged (spigotted) on the tailings infiltrates into the tailings pile. This fluid recharges the brine mound (brine storage), located at the base of the pile, allowing the pile to act as an arificial aquifer. The mound can be a significant factor in determining brine movement into the underlying aquifers especially since the head for a given height of fluid, exceeds that of freshwater due to its greater density. While spigotting is on-going the mound has been reported as high as 7 m, however it is not known to what extent precipitation alone charges the mound (Shook and Reid 1986). An understanding of the size of the driving head is important in determining the potential for downward movement of brine from an abandoned pile.

Pile drainage is by seepage, and flow through large cavities (karsts). The relative importance of these two processes and the formation and extent of the karsting is unknown. Most knowledge is anecdotal. The Soviets (Bogomolov et al.1977) speculate that the karsting occurs close to the surface due to increased density of the tails with depth. In Saskatchewan where cavities have been observed discharging on surface, as well as at the base of pile it has been speculated that the latter might be due to upward movement of freshwater from surficial aquifers (Maathuis and van der Kamp1983). Karsting is also caused by spigotting of undersaturated brine which instead of flowing down the decant slope, bores through the pile just below the mouth of the spigot to surface down slope. It is not known if karsting is a phenomena of active tailings only. Although Maathuis and vander Kamp (1983) speculated that cavities are formed at the base of the pile, the upward movement of freshwater will likely cease as pore pressures from rapid pile build up, dissipate.

Exactly where a pile discharges its brine is open to speculation. Discharge has been reported in the U.S.S.R. to be inhibited at the base of the pile due to the development of a dense and impermeable zone brought about by compression, and precipitation of salt in voids as a result of cooling with depth (Klement'yev et al. 1974). This however does not appear to be the case in Saskatchewan. There is evidence that PCS's Rocanville tails pile, which at 60 m in height, the tallest potash tailings pile in Saskatchewan, lacks an impermeable base. Whether this is due to general permeability of the tailings or to karst cavities is unknown. The head developed in the brine mound appears to have resulted in downward movement of brine into the surficial and and first intertill aquifers (10 m depth) (Hart 1985a).

Site Characteristics and Brine Pathways

To be effective, containment and decommissioning strategies must be based on a thorough understanding of the stratigraphy and the hydrogeological regime of the waste disposal site. Little information appears in the literature concerning siting conditions for potash waste management areas outside Saskatchewan.

Potash facilities in Saskatchewan are sited on a complex glaciated landscape (Fig 5), involving alternating layers of coarse and fine textured till deposits . The sands and gravels of the stratified drift may occur as surficial, intertill or intratill deposits (Clifton and Sauer 1983). The coarse textured deposits serve as aquifers while the finer textured till layers are relatively resistant to fluid movement, acting as aquitards. In most cases the surficial deposits are fairly permeable and are underlain by tighter soils (Maathuis and van der Kamp 1984, 1983).

Potash facilities are hydrologically situated in recharge or discharge positions (Tallin 1984) (Fig 6). Recharge sites are characterized by movement of surface and groundwater away from the tails pile and ponds. Flow is directed towards the waste management area at discharge sites preventing escape of contaminants. An intermediate situation also exits in which the brine tends to move away from the disposal site via the surficial aquifer but groundwater flowing upward from underlying aquifers prevents downward movement of brine. Most of Saskatchewan potash mines are sited on recharge positions, with the underlying aquifers serving as potential vectors for contaminant transfer.

Migration of brine occurs at most, if not all potash waste management areas, often with serious consequence. In French Alsace, Taleb and Valentin (1975) determined that the 10 potash waste piles which total about 200 Mt have seriously contaminated drinking water up to 25 km away. In addition the French operations contribute to the salinization of the Rhine by pumping 15 Mt/a into the system. Surface storage of salt wastes in the Soligorski area of Belorussia has resulted in groundwater contamination as well as salinization of agricultural soils (Klement'yev et al. 1976, Bogomolov et al. 1974, Turenkov and Zhugarev 1972, Bogomolov and Parfenova 1964, Kolpashnikov et al. 1970). According to Klement'yev et al (1976), contamination of the subsurface waters is spreading at a rate of 10 to 70 m/a. Brine release is not only of the insidious variety. In 1983, a brine pond dike failed in the Lvov area, releasing 4.6 m^3 of brine in a wall 6 m high. This dike failure resulted in serious contamination of the Dneister River, 15 km away resulting in the loss of fresh water for Odessa and Kishinev (Time 1983).

Extent and Impact of Brine Escape

In Saskatchewan, horizontal brine movement in the surficial aquifer ranges from very slight in the case of sites on clay deposits to 100 m/a for the more permeable sites located on recharge positions. The latter is most common in Saskatchewan (Hart 1985 a,b). Although considered to be inevitable at most sites, brine has not migrated into the deeper aquifers, except at PCS's mine at Rocanville in southeastern Saskatchewan. Fractures in the overlying till and a sufficiently large head in the tails pile appears to have resulted in contamination of the first interill aquifer, 10 m below surface.

To date groundwater contamination in Saskatchewan has been contained within a few kilometers of the waste management area. The potential does however exist at 8 of the 10 mines to seriously contaminate groundwater supplies and surface water bodies.

Brine Containment

Brine containment in Saskatchewan has concentrated on retarding the horizontal movement of brine in the surficial aquifer, where contamination is an immediate concern.

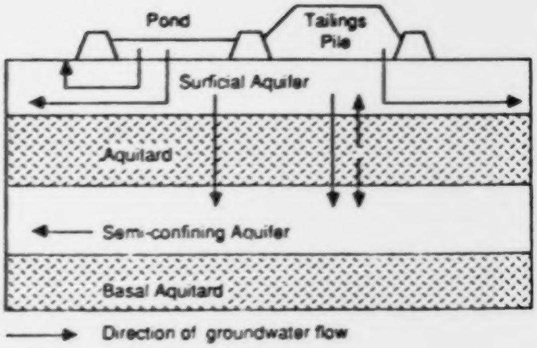

Figure 5: Typical stratigraphy associated with potash waste management area in Saskatchewan (after Maathuis 1989)

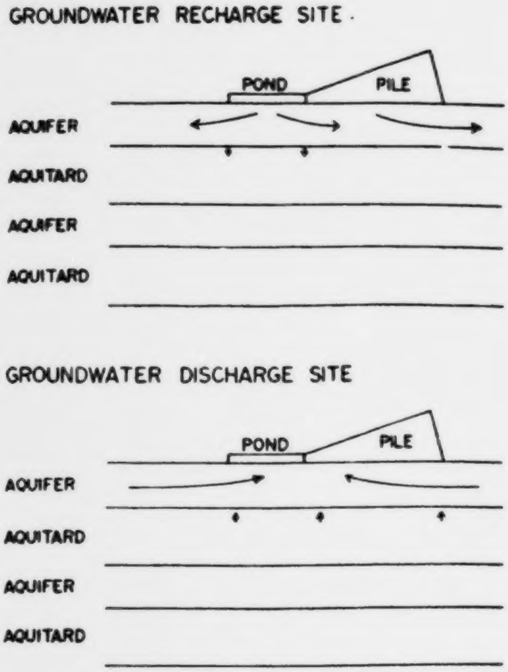

Figure 6: Hydrological positions of potash waste management facilities in Saskatchewan

Lining of brine ponds with synthetic liners, although a common practice in hazardous waste containment has only been attempted at one site in Saskatchewan. The first liners used proved to be totally inadequate , tearing easily and breaking down rapidly. A decade later a new liner, resistant to tearing and degradation due to ultraviolet radiation was installed in a small holding pond at PCS Rocanville. Its efficacy has not been evaluated (Hart 1985b).

Although an extensive system of dikes forms the core of all brine containment, it is usually backed up by one or more passive or active containment efforts (Fig. 7).

To be effective a dike must be constructed of material of low permeability, penetrating into the underlying aquitard. Keys or cut-offs are frequently lacking or have failed to penetrate the underlying aquitard. Ditches located peripheral to the dikes at four of Saskatchewan' s potash mines collect brine that has seeped through the dikes. As with keyed dikes, to be most effective the ditch must be cut down into the aquitard. Buried drains which are simply a more sophisticated ditch, have been installed at three sites and appear to have greatly restricted brine movement at two of the sites.

Slurry trenches are designed to retard brine movement in a similar fashion to keyed dikes. They differ, in that following excavation, the ditch is filled with a sem-liquid material of low permeability as opposed to an earth fill of low mositure content. Although common in hazardous waste containment, slurry trenches have been used in only one instance in the potash industry. Its poor performance which as in the case of failed cutoffs was likely due in part to inadequate penetration of the aquitard (Hart 1985b).

Although keyed dikes, ditches and drains have been used in Saskatchewan, to contain brine within the surficial aquifer. It is impractical to utilize these mitigation efforts in the deeper aquifers. Hydrodynamic containment, which involves pumping the affected aquifer, has been successful at PCS Rocanville. The wells have reduced movement of brine from 53 m/a to 3 m/a (Hart 1985b).

Saskatchewan's Potash Waste Disposal Options

During a conventional potash mine's operational life of about 65 years, 200 Mt of ore will be extracted resulting in more than 130 Mt of salt waste. Most will be stored on surface with the resulting tails pile and brine ponds covering about 8 km^2 at each of the 10 sites. By the time all economically recoverable ore, estimated to be from 7 000 to 14 000 Mt KCl (The British Sulfur Corporation 1985, Sheldrick and Stier 1978) has been extracted by conventional mining techniques, 14 000 to 28 000 Mt of salt waste will have been generated. If salt wastes are handled as they are today, this translates into 100 to 200 tails piles and associated brine ponds occupying up to 1 600 km^2 of agricultural land. Saskatchewan has total reserves of 100 000 Mt KCl, if the potash is extracted by solution mining (The British Sulfur Corporation 1985). If the salt waste is disposed of on the surface, this could result in 600 waste management areas, occupying nearly 5 000 km^2.

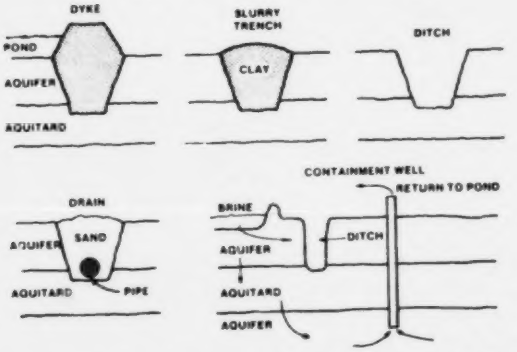

Figure 7. Brine containment structure in the Saskatchewan potash industry.

A number of decommissioning options have been proposed:

1) Marketing Salt

Opportunities to dispose of salt waste through marketing are very limited. Saskatchewan's annual salt waste production due to potash mining (20 Mt), if marketed represents 15% of the world's commercial salt production. The Canadian prairies sell about 700 000 t/a of which 300 000 t/a is derived from potash processing. Abundance of world supply and low value of salt combined with the high cost of transportation to market, preclude any significant expansion in salt sales from the prairies.

2) Underground Disposal

Although seemingly an obvious answer to the waste disposal dilemma, underground disposal is not the panacea if first appears to be. There are a number of limitations: 1) The receiving ore body must be stable, allowing for backfilling without catastrophic collapse; 2) At best only 70 to 80% of the waste can be returned to the mine workings due to expansion during processing and the need for an extensive network of travel ways; 3) The waste presently on surface, which in Saskatchewan is about 250 Mt, cannot be returned to the mine since collapse has eliminated most of the openings.

3) Abandonment

It may be possible to simply abandon a tailings pile. In the case of a discharge location, the area impacted will be limited to the discharge basin, however the majority of Saskatchewan's potash facilities are situated on recharge sites. At these sites the brine release from the pile must not exceed the receiving aquifer's ability to safely absorb salt. An acceptable level of discharge will depend on the initial ground water quality and its intended use. It is also essential that impact, at the aquifers point of discharge must be considered as well.

Precipitation, and groundwater interaction with the pile and the brine pond largely determine the rate of release of brine from the waste management area. Evaporation in the arid prairie environment potentially accounts for all the precipitation falling on the brine pond and much of that which is discharged into the pond from the tailings pile. Although evaporation from an unweathered pile is minimal, the development of a insol rich surface of low permeability in response to pile leaching could result in increased evaporation due to longer surface residence time (Hart 1988). It would also result in an increase in brine level in the pile and a subsequent decrease in the driving head.

Brine generation from dissolution by groundwater at the base of the pile, could be reduced by construction of keyed dykes, drains and ditches located upstream of the waste management area, deflecting or intercepting groundwater moving towards the tailings and brine pond.

After abandonment brine escape might actually increase due to pore pressure decline in the foundation soils under the tailings pile.

4) Dissolution and Injection of Brine

If environmentally acceptable, the injection of waste brine could continue to account for a significant proportion of the brine generated at an active mine site. It is also feasible as part of the decommissioning strategy over the long term. In both cases the rate of salt disposal could be increased by dissolving salt in addition to that brought about by precipitation. It is unlikely, considering the volume of water required (4 000 l/t salt) and the increasing demand for fresh water, that water suitable for alternative use would be utilized to dissolve salt tailings. This has led Cominco, west of Saskatoon to investigate using moderately saline water for this purpose. Water from the Blairmore formation, about 500 m below surface would be used to dissolve tailings and then be pumped back into the formation.

As noted earlier, the impact on the point of discharge for the Blairmore and the deeper receiving aquifers has not been assessed.

5) Solution Mining

Of the 10 Saskatchewan potash mines only Kalium near Regina is successfully extracting KCl by solution mining. Although a large pile has been generated there is some evidence that it will be gradually returned to the mine and the process altered so that salt waste need not be stored on the surface. Recently, cessation of mining due to flooding, a concern for most of Saskatchewan's potash mines, occcured at Potash Company of Saskatchewan's (PCA) mine,east of Saskatoon. This prompted the company to convert to solution mining. When operational, it is hoped that the tailings presently on surface, as well as those generated during solution mining, can be returned underground. Surface subsidence may be a concern since solution extraction in a conventional mine, will as intended remove the ore which previoulsy served as support pillars.

If the conversion from conventional mining to solution extraction is practical and economical, other mines are likely to follow suit. Considering the much larger reserves available to solution mining and the potential for a much smaller environmental impact, it is possible that all future mines will utilize solution extraction.

6) Reclamation - Revegetation and Capping

Regardless of which decommissioning option or combination of options is chosen, potash waste management areas must eventually be reclaimed. Due either to their areal extent and the proximity to uncontaminated ground and surface water, established methods of desalization are not practical. Leaching for instance, the most effective means of reclaiming severely saline soils (White and deJong 1975) would not only involve large quanities of fresh water but also result in the contamination of groundwater as the salt leached into the undulying aquifers.

North American producers have not attempted to reclaim potash tailings piles although some work has been done on the severely contaminated areas adjacent to the tailings pile. Thorpe (1989) experimented with two amendments in an effort to establish a vegetation cover over barren saline soil adjacent to a potash brine pond. He determined that under natural prairie conditions, upward migration of salts rapidly contaminated the 30 cm soil cover, as well as a similar depth of sewage sludge. Modelling revealed that even 150 cm of either material would be rapidly contaminated by the upward capillary movement of salts from the underlying saline soils.

The literature does not report any reclamation efforts in the Soviet Union, but does refer to minor successes in East Germany. Heinz and Fiedler (1979) reported the establishment of sparse, drough tolerant species on potash tailings in the district of the southern Hartz Mountains. These tailings unlike those in North America have developed a 0.5 to 1 m thick layer of salt-free insols. Pot experiments (Heinz and Fiedler 1981) using only 25 cm of salt free insol revealed the plants perished when the roots contacted the underlying salt wastes. Survival appeared to be related to the depth of the salt-free zone and root avoidance of the salt tailings. Initial success in establishing woody vegetation was also reported in East Germany by (Trillmich 1978).

Due to its arid environment, it is unlikely that a salt-free cover of insols will develop in Saskatchewan. The insol cover would likely remain saline due to capillary movement of salts from the underlying potash wastes..

Caps made of synthetics or soil are an option considered for tailings piles and associated land, severely contaminated by brine (Fig. 8). In order to be effective the cap must not only restrict downward movement of precipitation but also upward migration of salts. In the case of a tailings cap, water must be prevented from reaching the salt surface which would result in dissolution of the tails and collapse of the cover. A covering over brine contaminated land does not have to be impermeable, since a controlled release of salts into the underlying aquifer is acceptable. Upward capillary movement is not desirable in either situation.

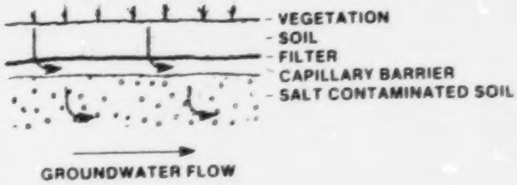

Figure 8. Soil - vegetation cap over salt contaminated soil.

Since a cap must be effective for hundreds if not thousands of years, synthetic membranes are not likely suitable due to their short life expectancy. A "natural" cap comprised of soil and maintained by a vegetation cover is likely to be more resilient.

Soil blankets are commonly employed in tailings reclamation, and decommissioning of industrial waste disposal sites (Marshall 1983). The major concern using this approach has been the upward migration of undesirable materials through the soil cover. This has led to contamination of the cap and the rooting zone, eventually disrupting the vegetation, resulting in cover loss through erosion. Arid regions such as the prairies where potential evaporation exceeds precipitation are especially prone to this phenomenon, as demonstrated by Thorpe (1989).

An appropriate soil cover depth necessary to prevent capillary movement has not been established, although the literature indicates that it likely is in excess of 2 or 3 m (Chopiak and Chekerda 1982,Yamamoto 1982, White and de Jong 1975). Unfortunately even if an effective depth can be established, penetration of precipitation by percolation or along cracks will result in tailings dissolution and collapse. An underlying coase textured layer could serve as both a capillary barrier to reduce the likelihood of upward movement of contaminants from the tailings as well as a drain, preventing moisture penetration into the underlying tailings.

Considering the nature of the underlying salt tailings it is doubtful that capping would be suitable for potash tailings pile. However the concept does appear promising for reclamation of the brine ponds, and severely salt contaminated soils (Fig. 8) Limited penetration by precipitation to the underlying brine contaminated soil would be acceptable, since dissolution and collapse would not occur as would be the case on a salt tails pile. Limited penetration would actually be desirable, if long term desalinization of the underlying soil is intended.

Summary

1) Potassium, one of the three major plant nutrients was first mined in Germany in 1961.

2) Saskatchewan's reserves account for 70% of the world's conventionally mined potash ore.

3) Saskatchewan's annual production of 10 Mt of KCl results in 20 Mt of salt tailings and 10 to 20 M m^3 of brine stored on surface.

4) As long as a mine is operational and can support active brine containment measures such as pumped drains and ditches, and containment wells, ground water contamination can likely be kept to an acceptable level.

5) For new mines, surface storage of salt wastes, especially in a rechange position will no longer be acceptable in Saskatchewan, due to the potential for extensive ground and surface water contamination.

6) Neither potash tailings piles nor the associated salt contaminated land have ever been decommissioned or reclaimed .

7) Decommissioning of present facilities will be site specific and likely involve a number of options.

8) Standard methods of reclaiming saline lands are impractical. Reclamation of saline soils adjacent to potash tailings and associated with brine ponds will likely involve soil covers with capillary barriers.

9) Research is required to determine:
    -the capacity of both surficial and deep aquifers to receive brine.
    -long term changes in the rate of brine release from salt tailings
    -the feasibility of returning salt tailings underground.
    -the effectiveness of soil caps for reclaiming salt contaminated sites.

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EFFECTS OF PHOSPHOGYPSUM AND MAGNESIUM CHLORIDE AMENDMENTS ON ABANDONED BENTONITE MINE SPOILS[1]

by

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ABSTRACT. Reclamation of abandoned sodic bentonite mine spoils is difficult due to elevated salinity and sodicity, and high smectite clay content. These spoils readily disperse upon wetting resulting in minimal water infiltration and the formation of impermeable surface crusts. Chemical amendments have recently been shown to be effective in ameliorating the adverse physicochemical properties inherent to these abandoned spoils. Experimental field plots were implemented to investigate the effectiveness of phosphogypsum and magnesium chloride brine as spoil amendments. These materials are low cost industrial by-products.

Analysis of amendment chemical constituents indicated that the phosphogypsum was 82.1% $CaSO_4 2H_2O$ and the magnesium chloride brine was 40.8% $MgCl_2$. The phosphogypsum was enriched in silver, cadmium, and selenium. However, amendment incorporation results in approximately 110:1 dilution which should prevent trace element accumulations.

After two growing seasons, application of these amendments resulted in reduced SAR and saturation percentage, and improved water infiltration. Improvements in these minesoil physicochemical parameters indicates that a more desirable plant growth medium is being developed.

Additional Key Words: Bentonite spoil reclamation, physicochemical properties, chemical amendments, trace elements, industrial by-products.

Introduction

Swelling capacity and thixotropic properties make bentonite a valued industrial mineral. These properties are enhanced when sodium is the dominant adsorbed cation. Because of the wide variety of commercial uses, bentonite has been mined for many years in the Northern Great Plains. The tri-state region of Montana, Wyoming, and South Dakota contains approximately 90% of the worlds economically minable deposits of high-grade sodium bentonite (Romo 1981).

Prior to the enactment of reclamation laws governing bentonite mining in the early 1970's, mined areas were left totally unreclaimed. An estimated 16,000 to 26,000 hectares of abandoned bentonite spoils are the result of pre-regulation mining activities (Smith et al. 1985). The clayey, saline-sodic nature of these spoils create adverse physicochemical properties. When the spoil receives precipitation, the combination of smectite clay mineralogy and high SAR (sodium adsorption ratio) result in spoil swell from clay dispersion. Mine spoil swelling processes substantially reduce hydraulic conductivity and permeability, and result in the formation of surface crusts that restrict seedling emergence. Due to these adverse conditions, invasion of native plant species is precluded and revegetation is difficult.

Bentonite reclamation technology was limited even into the 1980's. Sieg et al. (1983) found that topsoiling alone was not adequate for successful reclamation of abandoned bentonite spoils. Encouraging results have been reported using organic amendments. Wood residue amendment is known to improve vegetative production on bentonite spoils (Schuman and Sedbrook

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1984). Dollhopf et al. (1988) reported increases in long-term forage production using manure as an amendment. However, the ability of organic amendments to ameliorate long-term spoil physicochemical problems is uncertain. Anselmi (1986) reported that wood residue amendment did not alleviate the sodium problem in bentonite spoils.

Chemical amendments which supply calcium ions have been utilized for reclamation of sodic mine spoils. Calcium ions are strongly adsorbed and replace sodium on cation exchange sites. Through this mechanism, clay dispersion is reduced and spoil physicochemical properties are improved. Chemical amendment use significantly increases reclamation costs. Therefore, the identification of effective and low cost amendments is needed.

Amendments

Phosphogypsum

Phosphogypsum is a by-product of the phosphate fertilizer industry. Phosphate ore containing calcium is processed with sulfuric acid (H_2SO_4). Gypsum ($CaSO_4 2H_2O$) is precipitated as a silt sized (.002-.05mm) waste product. Phosphogypsum consists of the gypsum tailings material (80-99% $CaSO_4 2H_2O$), mineral impurities, and less than 1% phosphate (P_2O_5) (Keren and Shainberg 1981). Thousands of tons are produced annually in the United States with no apparent market.

In semi-arid environments, dissolution of agricultural (mined) gypsum is slow when applied to non-irrigated sodic minesoils. Because of the silt particle size, phosphogypsum has much more surface area than agricultural gypsum at a given fragment size (Keren and Shainberg 1981). These researchers found that due to the increased surface area, phosphogypsum has approximately ten times the dissolution rate as agricultural gypsum. Increased dissolution enables phosphogypsum to supply exchangeable calcium at a much faster rate.

Incorporation of phosphogypsum into the spoil profile can result in improved physicochemical properties. Gal et al. (1984) reported that phosphogypsum application reduced clay dispersion at the soil surface helping to prevent crust formation. Kazman et al. (1983) found that incorporated phosphogypsum prevented the sharp reduction in infiltration as the soil profile became wet.

Magnesium Chloride Brine

Magnesium chloride brine is produced as a by-product at table salt ($NaCl_2$) evaporation facilities. The brine consists of 35 to 45% $MgCl_2$, with minimal amounts of calcium, sodium, potassium, nitrate, and sulfate occurring as impurities.

As divalent alkaline earth metals, magnesium and calcium possess similar properties. Richards (1969) classified calcium and magnesium as similar ions important in soil structure development. Magnesium effectively replaces sodium from cation exchange sites (Arora and Coleman 1979).

Calcium chloride is a well known, effective amendment for sodic soils. The high solubility of calcium chloride (745 g/L) has proven to be the key to it's effectiveness. Magnesium chloride solubility (542 g/L) is also very high compared to agricultural gypsum (2.4 g/L).

Similar properties give magnesium chloride the potential to be as effective as calcium chloride in sodic soil reclamation. However, the only known field research using magnesium chloride as a soil amendment occurred in the Soviet Union. In this study, Papinyan (1980) reported significant soil ESP (exchangeable sodium percentage) reductions and improved soil-water relationships when magnesium chloride was used to amend sodic soil.

Plant growth is thought to be adversely affected by a low Ca^{2+}/Mg^{2+} ratio in the soil. Bohn et al. (1985) stated that high magnesium concentration may repress calcium uptake. Application of magnesium chloride brine as an amendment will elevate magnesium levels. Although there is potential for plant growth problems, Simson et al. (1979) found that satisfactory plant growth could be maintained between Ca^{2+}/Mg^{2+} ratios of 0.8 to 5.0.

Materials and Methods

In May of 1986, field plots were implemented near Belle Fourche, South Dakota on abandoned sodic bentonite mine spoils. Test plots were located directly adjacent to a 1980 bentonite field study (Dollhopf and Bauman 1981). The spoil material consisted predominantly of the Belle Fourche Shale. Precipitation in the area averages 36.7 cm/yr. Dominant plant species on undisturbed native rangeland are big sagebrush (Artemisia tridentata) and western wheatgrass

(Agropyron smithii). Bentonite mining in the area began in the early 1900's and is currently active.

Representative samples of each chemical amendment were taken prior to application for analysis of purity and total trace element concentrations by method 3050 (EPA 1982). Spoil core samples were taken before plot implementation to help characterize the site.

Unamended Mine Spoil Characterization

The test plots were located in an area of previously leveled spoil which was found to be homogeneous in an earlier study (Dollhopf and Bauman 1981). Insufficient space in the leveled area prevented new control plots from being implemented. Therefore, values for unamended spoil physicochemical properties were developed using all available data from the site. These data include SAR, EC, and saturation percentage values from several data sets obtained over a 7 year period.

Plot Implementation and Sampling Procedures

Test plot implementation began with chisel plowing of the plot area. Six, 5 x 15 m plots were staked in a block design with three replications of phosphogypsum (40.4 mt/ha) and three replications of magnesium chloride brine (36.2 mt/ha). Amendments were manually applied followed by rototilling for incorporation. Test plots were broadcast seeded, and mulched. Application rates for the chemical amendments were stoichiometrically calculated to potentially reduce SAR by 20 units (Smith 1988). This reclamation goal, if attained, would remove these spoils from the sodic classification.

Two, 0 to 35 cm core samples were taken from each plot in September of 1986 (4 months following plot implementation) and in July of 1987 (14 months following plot implementation). For each plot, core samples were divided into four depth increments and composited. Depth increments were 0 to 5 cm, 5 to 10 cm, 10 to 20 cm, and 20 to 35 cm.

In the laboratory, saturation percentage of core samples was determined by methods 26 and 27b (Richards 1969). Saturated paste extracts were evacuated from each sample for determination of SAR and EC (electrical conductivity).

In July of 1987, infiltration rates were measured on the phosphogypsum and magnesium chloride brine treated plots, and at 3 random locations on unamended spoil directly adjacent to each treatment replication. An infiltrometer built from construction plans presented in Meeuwig (1971) was used to simulate rainfall at the rate of 12 cm/hr. Runoff was measured over 5 minute intervals and values were used to determine infiltration rates.

To provide statistical summarization and comparison, analysis of variance (ANOVA) was conducted on all data sets. Least significant difference (LSD) at a 95% confidence interval was calculated for mean values in each data set. Coefficients from LSD calculations are included in Tables 2-4.

Results and Discussion

Amendment Chemical Characteristics

Results from amendment analyses indicated that the applied phosphogypsum was 82.1 % $CaSO_4 2H_20$. The magnesium chloride brine contained 40.8% $MgCl_2$. In the phosphogypsum amendment, total silver (Ag) concentration was 15% greater than the suspected phytotoxic level (EPA 1987b). Total cadmium (Cd) and selenium (Se) concentrations were enriched above expected background levels in soil (Kabata-Pendias and Pendias 1984, Shacklette and Boerngen 1984). Total concentrations of the other analyzed trace elements were within the normal range for soils (Table 1). No enrichment of trace elements was detected in the magnesium chloride brine.

Assuming that 1 acre-ft of spoil weighs 4 million pounds, incorporation (35 cm) of the phosphogypsum amendment results in dilution of 40.4 metric tons (mt) into 4480 (mt) of spoil within 1 hectare. This represents a dilution ratio of approximately 110:1. Although several trace elements were enriched in the phosphogypsum, amendment dilution minimizes the potential for plant growth problems.

Radium 226 occurs in much of the phosphate ore from the Western United States. Phosphogypsum tailings produced in Idaho and Utah are reported to have concentrations of radium 226 exceeding the U.S. EPA suspect level of 5 picocuries/gram (Range Inventory and Analysis 1986). In a Wyoming study, 12 inch incorporation of phosphogypsum amendment (35.5 mt/ha) with an average of 26 picocuries/gram radium 226, resulted in no significant increase in radium 226 levels compared to background levels (Range Inventory and Analysis 1986).

Table 1. Trace element total concentrations[1] in phosphogypsum and magnesium chloride brine amendments.

ELEMENT	BACKGROUND LEVEL[2]-SOURCE[3]	PHYTOTOXIC LEVEL-SOURCE	PHOS-GYPSUM	MAGNESIUM CHLORIDE
Silver	.03-.09 g	2 b	2.3	.36
Aluminum	57,000 i	---	1380.0	.2
Arsenic	3.6-8.8 d	100 a	1.5	1.4
Barium	265-835 c	---	73.0	<1.0
Beryllium	1.6 c	10 f	<.5	.22
Cadmium	.07-1.1 c	100 a	10.0	.95
Cobalt	8.2 c	50 f	<1.0	.01
Chromium	20-85 d	100 f	34.0	.08
Copper	10-50 b	100 b	9.5	.3
Iron	27,500 c	---	330.0	28.8
Mercury	.04-.28 d	5 b	<.1	.004
Manganese	260-840 d	3000 e	3.3	1.32
Nickel	19 c	100 f	6.6	.08
Lead	17-26 d	1000 a	4.4	.06
Antimony	.9 c	10 f	<1.0	<1.0
Selenium	.2-.5 d	10 b	5.0	<.005
Tin	.6-1.7 d	50 f	<10.0	---
Thallium	.02-2.8 h	10 b	<1.0	.1
Vanadium	58 d	100 f	27.0	3.9
Zinc	34-83.5 d	500 a	37.0	4.0

[1] -Concentrations given in ppm on dry weight basis.

[2] - Background level for soils.

[3] - Sources are: **a** is EPA (1987a); **b** is EPA (1987b); **c** is Kabata-Pendias and Pendias (1984); **d** is Shacklette and Boerngen (1984); **e** is Kovalskiy (1974); **f** is Kabata-Pendias (1979); **g** is Smith and Carson (1977a); **h** is Smith and Carson (1977b); and **i** is Tidball and Severson (1975).

Unamended Mine Spoil Physicochemical Characteristics

Representative unamended spoil SAR and EC across the research site were determined to be 33.8 and 8.0 dS/m, respectively. The representative value for unamended spoil saturation percentage was 127. The preceding mean values were developed using data sets from 1980 pre-amendment sampling, 1986 sampling of the 1980 control plots, and pre-amendment sampling for this study.

Minesoil Sodium Adsorption Ratio (SAR)

Four months (1986) following amendment application, the SAR on magnesium chloride plots was significantly less than on spoil or phosphogypsum plots at 0 to 5 cm (Table 2). Little change in SAR was noted on amended plots over the 10 to 35 cm depth at this time. The SAR reduction on magnesium chloride plots suggests that this amendment is highly effective within 4 months following application.

Fourteen months (1987) following amendment application, both magnesium chloride and phosphogypsum treated plots (0-5 cm) were significantly less in SAR compared to unamended spoil (Table 2). The SAR reduction of 9.3 units on phosphogypsum plots (0-5 cm) corresponds to 46% of the SAR reduction goal. On magnesium chloride plots, the reduction of 12.5 SAR units indicates 62% effectiveness. Over the 5 to 35 cm depth, SAR reductions were also detected on treated plots.

Table 2. Minesoil SAR values[1] at the Belle Fourche site.

YEAR	TREATMENT	SAR 0-5cm	5-10cm	10-20cm	20-35cm
1986	Phos-gyp	30.7 b[2]	31.6 a	28.4 a	29.3 a
	$MgCl_2$	20.4 a	32.0 a	33.8 a	35.2 a
	Spoil	33.8 b	33.8 a	33.8 a	33.8 a
1987	Phos-gyp	24.5 a	29.3 a	28.4 ab	27.8 a
	$MgCl_2$	21.3 a	26.3 a	26.3 a	31.7 a
	Spoil	33.8 b	33.8 a	33.8 b	33.8 a

[1] - Values from treated plots represent the mean of 3 replications. Spoil values represent the overall mean from 3 data sets.

[2] - Means followed by the same letter in the same column indicate no significant difference ($P=0.05$).

Magnesium chloride brine appears to be slightly more effective than phosphogypsum in reducing SAR over the initial 14 month period. Prompt dissolution enables an amendment to react sooner within the spoil system. The liquid physical nature of magnesium chloride brine provides a temporary solution in the minesoil. Sodium replacement reactions are possible immediately following amendment application.

Minesoil SAR improvements were most apparent near the surface. As physical properties such as structure and permeability improve as a function of reduced SAR, more water will infiltrate into the profile. Progressively, minesoil physicochemical improvements should occur at depth as a function of increased infiltration.

Minesoil Electrical Conductivity (EC)

Application of either phosphogypsum or magnesium chloride brine increased minesoil salinity levels compared to the unamended spoil EC value of 8.0

dS/m. Four months (1986) following amendment application, EC values from saturated paste extracts were significantly greater on magnesium chloride brine treated plots (0-20 cm) compared to unamended spoil (Table 3). At the 0 to 5 cm depth, salinity increased by 39% on phosphogypsum plots and 112% on magnesium chloride plots.

Fourteen months (1987) following amendment application, EC values on magnesium chloride plots were significantly greater than unamended spoil over the entire amended depth (Table 3). At the 0 to 5 cm depth, EC was 57% greater on magnesium chloride plots compared to phosphogypsum plots.

Table 3. Minesoil electrical conductivity (EC) values[1] at the Belle Fourche site.

YEAR	TREATMENT	EC (dS/m) 0-5cm	5-10cm	10-20cm	20-35cm
1986	Phos-gyp	11.1 ab[2]	10.9 a	9.5 ab	8.9 a
	MgCl$_2$	17.0 b	19.1 b	12.4 b	7.6 a
	Spoil[1]	8.0 a	8.0 a	8.0 a	8.0 a
1987	Phos-gyp	10.1 ab	11.6 ab	11.6 b	10.0 ab
	MgCl$_2$	15.9 b	14.0 b	12.8 b	12.9 b
	Spoil[1]	8.0 a	8.0 a	8.0 a	8.0 a

[1] - Values from treated plots represent the mean of 3 replications. Spoil values represent the overall mean from 3 data sets.

[2] - Means followed by the same letter in the same column indicate no significant difference (P=0.05).

Over the remainder of the amended profile, magnesium chloride plots had EC values consistently greater than phosphogypsum plots, but to a lesser degree than at 0-5 cm. The range in EC on magnesium chloride plots indicated that after 14 months salinity remained 60 to 99% higher than pre-amendment levels.

Although high salinity inhibits water uptake by plants, there was a net improvement in the plant growth medium due to improved minesoil physicochemical properties.

Minesoil Saturation Percentage

Saturation percentage determinations were performed on core samples taken in the summer of 1987 to relate improvements in minesoil SAR to physical properties. Saturation percentage gives an indication of the severity of soil structure breakdown due to clay mineral dispersion. In a dispersed condition, pore space is reduced or eliminated decreasing water transmission through the minesoil. Reduced values for saturation percentage correspond with improved minesoil physical properties.

Saturation percentage was significantly less on both phosphogypsum and magnesium chloride brine treated plots (0-5 cm) compared to unamended spoil (Table 4). In comparing amended test plots, saturation percentage was significantly less on magnesium chloride brine treated plots (0-5 cm) at 73, compared to 103 on phosphogypsum treated plots. These values indicate a 42% reduction on magnesium chloride plots and a 19% reduction on phosphogypsum plots over 0 to 5 cm. Saturation percentage was also reduced throughout the 5-35 cm depth for both treatments suggesting that the severity of swelling processes had been decreased.

Table 4. Summer, 1987 minesoil saturation percentage[1] at the Belle Fourche site.

TREATMENT	SOIL DEPTH (cm) 0-5	5-10	10-20	20-35
Phosphogypsum	103 b[2]	111 b	128 b	122 a
MgCl$_2$	73 a	80 a	90 a	95 a
Spoil[1]	127 c	127 b	127 b	127 a

[1] - Values from treated plots represent the mean of 3 replications. Spoil values represent the overall mean from 2 data sets.

[2] - Means followed by the same letter in the same column indicate no significant difference (P=0.05).

Minesoil Infiltration Rates

The infiltration rate study was conducted to determine if the applied amendments increased infiltration into the minesoil profile. Sodic mine spoils typically allow near normal infiltration initially, but exhibit dramatic infiltration rate reductions within a short time due to soil pore blockage from clay dispersion.

Results from the infiltration rate study indicate that infiltration rates improved on amended test plots (Figure 1). The 5 to 10, and especially the 10 to 15 minute infiltration rates clearly demonstrate the effects of the amendments. By 10 to 15 minutes, minimal infiltration was occurring on unamended spoil. Nearly all precipitation was being converted to runoff. Erosion potential increased and moisture needed in the root zone was lost. Over the same time period, substantial infiltration was occurring on the amended test plots. After 30 minutes of simulated rainfall, amended test plots maintained moderate (2-6 cm/hr) infiltration rates.

On unamended spoil, the infiltration rate dropped to 0.1 cm/hr.

Results from the infiltration rate study indicate that the combination of chisel plowing, chemical amendments, seeding, and straw mulch improved surface water infiltration into the minesoil. It is likely that a majority of the improvement in infiltration is due to the application of the chemical amendments. The effects of plowing and mulch may be minimized after 14 months due to minesoil shrink-swell processes and mulch decomposition. Reduced saturation percentages on amended plots suggest that water movement through the minesoil profile should increase.

Summary

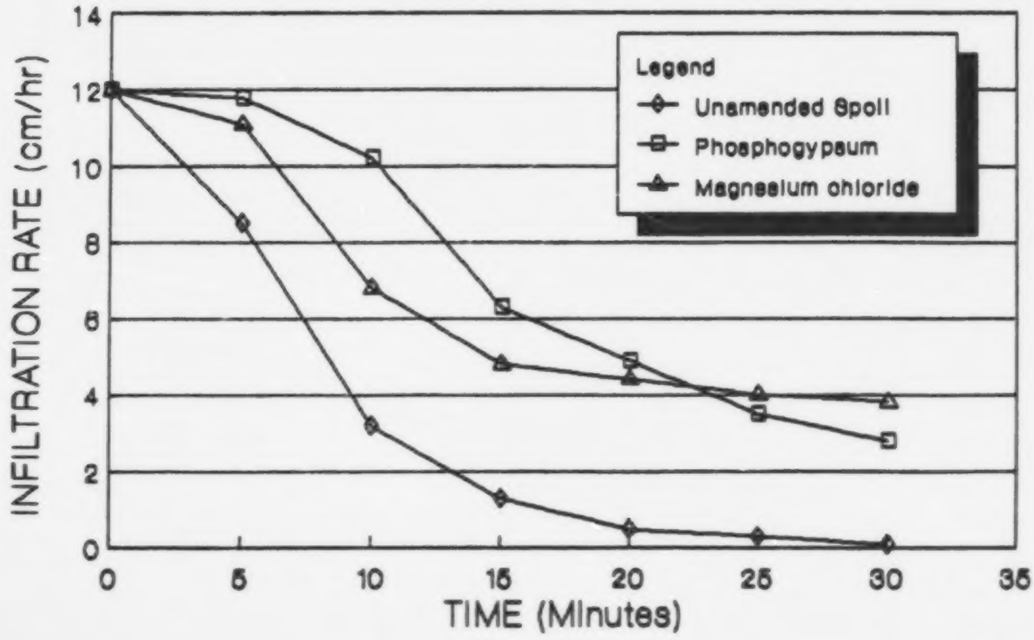
Application of either phosphogypsum (40.4 mt/ha) or magnesium chloride brine (36.2 mt/ha) in combination with chisel plowing, seeding, and mulch resulted in reduction of SAR and saturation percentage, particularly near the surface. Four months following amendment application, mean SAR on magnesium chloride brine treated plots (0-5 cm) declined significantly from an unamended spoil SAR of 33.8, to 20.4.

Fourteen months following amendment application, mean SAR (0-5 cm) was 21.3 on magnesium chloride treated plots and 24.5 on phosphogypsum treated plots. These SAR values were both significantly less than unamended spoil. Saturation percentage (0-5 cm) declined from an unamended spoil value of 127, to 73 and 103 on magnesium chloride and phosphogypsum plots, respectively. These results suggest that application of either amendment will result in SAR and saturation percentage reductions. However, these reductions occur more rapidly with the magnesium chloride brine amendment.

An initial rise in EC near the surface occurred following application of either amendment. Four months following amendment application, EC (0-10 cm) increased an average of 37% on phosphogypsum treated plots and 125% on magnesium chloride treated plots. After two growing seasons (14 months), EC appeared to be declining near the amended surface. However, limited data makes this trend difficult to confirm.

Minesoil infiltration rates were significantly increased by the application of either amendment. After 30 minutes of simulated rainfall, amended test plots maintained moderate (2-6 cm/hr) infiltration rates. Over the same time period, the infiltration rate on unamended spoil dropped to .1 cm/hr.

Figure 1. Minesoil infiltration rates over time at the Belle Fourche site.



The phosphogypsum amendment was enriched above background levels in cadmium and selenium, and contained silver at concentrations slightly above suspected phytotoxic levels. However, because of dilution by amendment incorporation, trace element accumulations are unlikely. No enrichments in trace elements were detected in the magnesium chloride brine. As industrial by-products, both phosphogypsum and magnesium chloride brine create disposal problems at processing facilities. Use of these materials to reclaim disturbed sites produces a two-fold reclamation success. As waste products, these amendments are considerably less expensive than their counterparts, mined gypsum and calcium chloride.

Abandoned sodium bentonite mine spoils are a difficult reclamation challenge requiring amendments that are effective, yet cost feasible. Phosphogypsum or magnesium chloride brine application to this minesoil decreased the SAR and saturation percentage, while improving infiltration rates. Fourteen months following plot implementation, the plant growth medium had been improved allowing vegetation to be well established.

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Soils and Overburden

Session Chairmen: G.W. Wendt and M.W. Pole

REVEGETATION POTENTIAL OF OVERBURDEN MATERIALS FROM KITTANNING COAL MINES[1]

by

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Abstract. Two independent revegetation studies were conducted on Kittanning overburden materials. Problems with acidity have often been encountered during reclamation of Kittanning coal mines in West Virginia, Maryland, and Pennsylvania. The first study was a field study in which part of a regraded area was covered with local topsoil, but the rest of the area was covered with a topsoil substitute obtained from sandstone in the overburden. This substitute had not been analyzed before use. In this study, the topsoil supported vegetation better than the substitute, since the substitute was acid-producing material. In the second study, minesoil profiles were constructed in 30-cm diameter, 100-cm deep PVC columns. Spoil was covered with topsoil, crushed alkaline sandstone, or a mixture of the topsoil and sandstone. In this study the sandstone, mixture, and spoil with no soil cover supported better vegetative growth than the topsoil. Although Kittanning overburden strata are generally thought to be potentially toxic, the strata should be thoroughly characterized. This study indicates that not all overburden strata above Kittanning coal is toxic and that some has the potential of serving as topsoil substitute.

Additional Key Words: minesoil properties, topsoil, topsoil substitute.

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Introduction

The Kittanning coal seams (Upper, Middle and Lower), which formed in the Allegheny geologic formation of the Pennsylvanian period, are very important to the coal industry of West Virginia. The estimated original minable reserve of these three seams was 15.2 billion tons (Barlow 1974).

Kittanning coals are generally located in the northern coal field of West Virginia but are found near the "hinge line" which separates the northern and southern coal fields (Barlow 1974). These coals generally have high-sulfur (> 1.5% S) contents, and overburden materials associated with these seams commonly have high sulfur levels. Sites which are mined for these coals have a propensity to produce acid mine drainage (AMD) and acidic minesoils which are difficult to vegetate. Although some sites have been reported to be successfully reclaimed (Smith et al. 1974), others present major challenges to reclamationists.

Because of revegetation and acid mine drainage problems associated with Kittanning coal mining, the Director of the West Virginia Department of Natural Resources (WVDNR) appointed a group of scientists, coal operators and WVDNR personnel to study the problem. This group, called the Acid Mine Drainage Technical Advisory Committee (AMDTAC), was appointed in 1981. AMDTAC has been dissolved but some of the studies initiated by that group are continuing.

The purpose of this paper is to report some results of two of the AMDTAC studies. The primary objective of both studies was to evaluate the revegetation potential of various Kittanning overburden materials. A secondary objective was to determine if revegetation potential could be predicted by acid-base accounting procedures. The studies were conducted on Kittanning surface mines in the Buckhannon River watershed in Upshur County, West Virginia.

Materials and Methods

Study #1

The study site was a mountaintop surface mine where a 0.5-mm thick PVC liner was placed over 18 ha of acid-producing spoil in an effort to control AMD (Nicholas and Foree 1982; Caruccio and Geidel 1983). The purpose of this paper is to discuss the properties of the soils and vegetation above the liner.

Two cover materials, varying from 35 to 100 cm thick, were placed on the liner. Since a limited amount of native topsoil was available, a substitute material was used to cover part of the liner. The topsoil was derived from a stockpile of native soils [Dystrochrepts, Fragiudults, Hapludults (Soil Survey Staff 1975)], and the substitute consisted of crushed acid sandstone overburden. After placement of the cover materials, slopes ranged from 1 to 8%, near the top of the hill and from 11-25% on the sides.

Minesoils were sampled in October 1982 and August 1984 along transects established perpendicular to the contour. Since soil properties were not significantly different between 1982 and 1984, only 1984 data are presented. Soil pits were excavated to the liner at 55-m intervals along the transects. Nine topsoil and 14 substitute pits were described. Bulk soil samples were taken at 0-12 cm, 12-25 cm, 25-50 cm, and 50-75 cm from alternate pits in each transect for laboratory analyses.

The areal extent of each cover material was mapped to identify the minesoil series. Fiveblock [loamy-skeletal, mixed, nonacid, mesic Typic Udorthents (Soil Survey Staff, 1975)] and Sewell (loamy-skeletal, mixed, acid, mesic Typic Udorthents) were mapped on the topsoil. An unnamed series in the same family as Sewell was mapped on the substitute.

Both cover materials were amended with 27 Mg/ha (12 T/A) of limestone, 150 kg/ha of N, 90 kg/ha of P, and 125 kg/ha of K (100 lb 0-40-0 and 700 lb 19-19-19 per acre). Amendments were incorporated to a depth of 12 cm. The seeding mixture included 'Ky-31' tall fescue (*Festuca arundinacea* Schreb.), annual ryegrass (*Lolium multiflorum*), 'Empire' birdsfoot trefoil (*Lotus corniculatus* L.), alsike clover (*Trifolium hybridum*), and red clover (*Trifolium pratense*). Reclamation on the site was completed in June 1982.

Study #2

Simulated minesoil profiles were constructed on a West Virginia University farm in Monongalia County. The subsoil was collected from a stockpile of fragmented sandstone spoil from the Middle and Lower Kittanning coals at an active mine in Upshur County. Topsoil and a topsoil substitute were collected from a nearby inactive mine. The topsoil, a mixture of A, B, and C horizons [Fragiudults and Hapludults (Soil Survey Staff 1975)], was sampled from a stockpile. The topsoil substitute was a crushed alkaline sandstone which had been quarried from the coal overburden.

Containers for the simulated minesoil profiles were constructed from 30-cm diameter white PVC pipe. The pipe was cut into 98-cm long sections, and each section was placed vertically into a 10-cm thick bed of mortar sand to allow free drainage of water from the columns.

The minesoil profiles constructed within the containers were designed to represent a loamy-skeletal subsoil covered with topsoil materials of different thicknesses. Fragments greater than 7.6 cm in diameter were removed from the subsoil before placement in the container. After placement, the subsoil was compacted to achieve a penetrometer reading similar to that observed on a graded site prior to topsoiling.

Each profile was 91 cm thick and consisted of one of the following:

1. Spoil only;
2. Spoil with a covering of crushed sandstone at thicknesses of 15 cm, 30 cm, or 45 cm;
3. Spoil with a covering of stockpiled topsoil at thicknesses of 15 cm, 30 cm, or 45 cm;
4. Spoil with a covering of a 1:1 mixture of crushed sandstone and topsoil at thicknesses of 15 cm, 30 cm, or 45 cm.

Each treatment was replicated three times and incorporated into a randomized complete block design. The blocks were arrayed as parallel north-south rows with 4.9 m between rows and 3.1 m between containers.

Soils in all columns were fertilized with ammonium nitrate, triple superphosphate, and potassium chloride at a rate equivalent to 672 kg/ha (600 lb/A) of 10-20-10 blended fertilizer. The native topsoil, the only material requiring lime, was limed at the rate (5.5 T/A) recommended by the WVU Soil Testing Laboratory to raise the pH to 6.5 (Ghazi et al. 1978). Both the fertilizer and limestone were incorporated to a depth of 15 cm.

In June 1983, all treatments were seeded at a rate equivalent to 22.4 kg/ha (20 lb/A) of tall fescue and 16.8 kg/ha (15 lb/A) of birdsfoot trefoil. Hay mulch was applied at a rate approximating 5.6 Mg/ha (2.5 T/A).

Laboratory Analyses

Minesoil properties for both studies were analyzed by the following procedures: pH (1:1), KCl exchangeable Al, ammonium acetate, exchangeable Ca, Mg, and K, cation exchange capacity (CEC) at pH 7.0 by ammonium saturation, organic carbon (OC) by acid-dichromate digestion, and electrical conductivity (EC) of the saturated paste extract (Soil Survey Staff 1972); total S, neutralization potential (NP), total N by Kjeldahl distillation, soil texture by the pipette method, and moisture retention at 33 and 1500 kPa pressures (Sobek et al. 1978); DTPA extractable Fe, Mn, Cu, and Zn (Lindsay and Norvel 1978); Bray I extractable P (Olsen and Sommers 1982); and liquid limit (LL) and plasticity index (PI) (American Society for Testing and Materials 1981).

Vegetation Evaluation

For study #1 the vegetative cover was estimated by a point frequency method (Raelson and McKee 1982) in September 1983 and 1984. A grid was superimposed over the site map and coordinate points were selected at random. The points were located in the field, and vegetation at these points was evaluated.

For study #2, vegetation establishment was evaluated by two methods. A stem count was made for each container for two growing seasons. The count was restricted to stems greater than 8 cm in height. At the end of the second growing season, an estimate of percent ground cover was included because all of the first season's vegetation died during the winter. Although vegetation returned to every container during the second season, much of the vegetation consisted of volunteer and weedy species, and the total number of stems was less than the first season.

Statistical Analyses

All statistics were performed using a SAS computer package containing ANOVA and Duncan's multiple range test (SAS Institute 1982). Kramer's adjustment was applied to those comparisons which had unequal group sizes.

Results

Study #1

Soil Properties. The topsoil and substitute had loam and sandy loam textures (Table 1). Rock fragments comprised 35 to 80% (avg 55%) of the volume of the substitute material and 25 to 60% (avg 35%) of the topsoil material. Sandstone was the dominant rock type, making up 90% or more of the rock fragments in both cover materials. While the substitute had a higher percentage of sand than the topsoil, both cover materials were similar in percent clay, moisture retention characteristics, LL, and PI (Table 1). Low MRD, LL, and PI values reflected the sandy nature of both soils.

Chemical properties of the topsoil and substitute sampled during the third year of the study are summarized in Table 2. Surface OC increased from 9 to 16 g/kg in the topsoil and from 8 to 11 g/kg in the substitute between the first and third years, respectively. Other chemical properties did not change significantly within the 3-yr period. In both materials, Ca, NP, and pH were

Table 1. Physical properties of the two materials used to cover the PVC liner.

Material	Clay	Sand	Moisture Retention 33 kPa	Moisture Retention 1500 kPa	MRD[1/]	LL	PI
	----------------	----------------	% by weight	----------------			
Topsoil	15.6	52.0	0.19	0.09	0.10	24	4
Substitute	13.1	60.1	0.16	0.08	0.08	20	2

[1/] MRD = 33 kPa - 1500 kPa.

Table 2. Chemical properties of the topsoil and substitute cover materials over the PVC liner three years after placement.

Depth	CEC	Extractable Ca	Extractable Al	EC	P	OC	S	NP $CaCO_3$ Equiv.	pH
cm	--cmol	(+)/kg--		ds/m	mg/kg	g/kg	%	kg/mg	
				Topsoil					
0-12	10.2a	13.0a	<0.1c	1.2cd	5.7ab	16a	0.05b	41.6a	6.8a
12-25	11.5a	4.4bc	0.7bc	1.5cd	5.4ab	13ab	0.06b	1.8b	5.0b
25-50	10.6a	4.9bc	0.4c	1.8bc	4.2ab	13ab	0.06b	2.1b	5.3b
50-75	9.0ab	2.3c	0.3c	0.8d	3.8ab	9cd	0.05b	1.1b	5.3b
				Substitute					
0-12	7.2bc	9.6ab	0.7bc	2.6b	11.0a	11bc	0.21a	26.2ab	5.2b
12-25	6.3c	3.3c	2.4a	3.8a	1.0b	7cd	0.24a	-1.6b	3.4c
25-50	6.0c	2.6c	2.6a	4.3a	1.4b	7cd	0.24a	-1.3b	3.4c
50-75	5.8c	2.1c	1.5b	3.7a	3.0b	6d	0.23a	-0.2b	3.9c

Column means followed by the same letter are not significantly different at the 0.05 level.

higher in the surface (0-12 cm) than in the subsurface (12-75 cm) because of lime additions. Liming resulted in lower Al, acidity, and EC levels in the surface than in the subsurface of the substitute. Both materials had a higher OC content in the surface than in the subsurface as a result of the accumulation of organic matter due to vegetation establishment, litter accumulation, and root growth. Cation exchange capacity, OC, and pH were higher in the topsoil, whereas Al, S, and EC were higher in the substitute. While both cover materials had low to very low agronomic levels of P, K, and Mg, the topsoil did not have the acid-related problems found in the substitute. The substitute had extremely-acid pH values, high levels of extractable Al, a deficiency of neutralizers, and high salt concentrations (as indicated by the EC). These data may be attributed to pyrite oxidation (Evangelou and Phillips 1984; Singh et al. 1982).

Vegetation and Root Growth. By the third growing season, the vegetative cover across the site was 69% (90% CI ± 6%). Vegetative cover was 30% greater on the topsoil than on the substitute (Table 3). Of the species present on the entire site, 50% were seeded grasses, 40% seeded legumes, and 10% volunteer species. The dominant species in the third growing season were tall fescue and birdsfoot trefoil. Legumes on the site increased in proportion to the grasses between the second and third growing seasons. The grass/legume ratio was 1:1 in the second growing season, compared to 1:3 in the third.

Table 3. Vegetative cover and root growth characteristics on the topsoil and substitute materials.

	Topsoil	Substitute
Vegetative cover (%)		
1984	93	61
90% CI$^+$	6	7
Depth of major root zone, cm		
1982	8	4
1984	10	7
Depth of maximum root growth, cm		
1982	14	7
1984	52	12

Most roots were concentrated in a shallow zone at the surface (Table 3). By the third growing season, root growth extended below the depth of lime and fertilizer incorporation in all 9 topsoil pits but in only 3 of 14 substitute pits. The average depth of maximum root growth in the topsoil more than tripled between the first and third growing seasons, and was over four times greater than the substitute.

Study #2

Characterization of Materials. The spoil material used in this study had been segregated by the mine operator as an acid producing material containing about 0.5% sulfur. Analysis revealed that this material was moderately high in total sulfur (Table 4), but it also had a high pH, high Ca level, and high NP, indicating no potential to produce acid. In addition, the spoil effervesced when diluted HCl was added. The sandstone was segregated as an alkaline topsoil substitute, but it did not effervesce with HCl. The topsoil held more water than the other materials (Table 5), because it had more clay.

Extractions of available Fe, Mn, Cu and Zn indicated that neither toxicities nor deficiencies of these micronutrients existed in any of the materials at the beginning of the study. All of the materials were extremely low in total nitrogen ($\leq$ 0.05%) and soil organic matter ($\leq$ 0.6%).

Vegetation Evaluation. Three months after seeding, both seeded species (fescue and trefoil) were established in all containers. During the first growing season, topsoil treatments were less successful in producing a vegetative cover than the other three

Table 4. Chemical properties of topsoil and substitute materials before treatment.

Material	Ca	Mg	K	Al	CEC	S	N.P.	pH
	----------cmol (+)/kg----------					%	g/kg	
Spoil	12.50	0.96	0.12	0.0	2.92	0.302	30.90	7.4
Sandstone	2.56	0.80	0.90	0.0	2.08	0.056	11.44	7.5
Topsoil	0.28	0.20	0.09	3.3	6.79	0.002	0.28	4.4
1:1 Mix	2.62	0.72	0.11	0.1	4.50	0.088	7.23	5.1

Table 5. Physical properties of topsoil and substitute materials before treatment.

Material	Sand	Silt	Clay	Moisture Retention 33kPa	Moisture Retention 1500kPa	MRD[1/]
	----------------% by weight------------------					
Spoil	68.7	19.2	12.1	11	3	8
Sandstone	75.3	16.2	8.5	9	2	7
Topsoil	37.8	42.6	19.6	22	7	15
1:1 Mix	61.8	25.2	13.0	15	5	10

[1/] MRD = 33kPa - 1500kPa.

soil materials (Table 6).

The vegetation parameters analyzed during the second growing season generally followed the trends observed in the first season (Table 6). Since the vegetation could not survive the winter, it was decided to discontinue collecting vegetation data after the second growing season.

Soil pH. When analyzed three years after treatment, pH of the surface samples (0-15 cm) of the sandstone, topsoil, and the 1:1 mixture appear to have remained constant (Table 7). The spoil pH appears to be lower after three years. When the columns were sampled after the fifth year, roots were observed to be proliferating through the total thickness of the spoil in all columns. Therefore, after five years, the spoil properties (data to be reported at a later date) were still promoting root growth.

Discussion

Study No. 1

The substitute was inferior to the topsoil for revegetation because of its acidic properties. These results have been corrobated by literature reports of Lower Kittaning coal seam overburden analyses (Smith et al.

Table 6. Growth of vegetation on topsoil and substitute materials for two growing seasons.

Material	Stems First Season	Stems Second Season	Cover Second Season
	No./column	No./column	%
Spoil	105	36	67
Sandstone	117	57	74
Topsoil	54	39	57
1:1 Mix	114	56	67

Table 7. pH of topsoil and substitute materials for a three-year period.

Material	Before Treatment	After Treatment 1YR	After Treatment 3YRS
Spoil	7.4	7.3	7.0
Sandstone	7.5	7.8	7.7
Topsoil	4.5	6.6	6.6
1:1 Mix	5.1	7.2	7.3

1974). Vegetation after three growing seasons was substantially better on the topsoil than on the substitute. At the end of the third growing season, only the vegetative cover on the topsoil met the West Virginia regulatory requirements of 90 percent ground cover on mined lands.

Results of this study indicate that when reclaiming areas mined for the Lower Kittaning coal or other seams within the Allegheny Geologic Formation, care should be taken in selecting alternative topsoil materials. If non-acidic materials are not available, deep incorporation of limestone is recommended for revegetation. If possible, limestone should be incorporated to a depth of 60 to 90 cm so that roots will proliferate the minesoil for water and nutrients. Since incorporation of limestone to these depths will be very difficult after regrading has been completed, it is recommended that limestone be mixed with the alternative topsoil materials as they are being graded to final contour.

Study #2

The results indicate that all of the materials studied were capable of establishing a vegetative cover provided they were amended with the recommended rates of fertilizer and lime. Thickness of the topsoil cover did not affect plant establishment or growth in this study. This may be due to the fact that the underlying spoil did not restrict root growth as originally anticipated. At the end of the study when the columns were sampled, it was noted that roots had penetrated throughout the spoil material. The only experimental parameter which appeared to affect plant growth and species composition was the type of soil material. Vegetation establishment was poorer on native topsoil than on crushed sandstone, mixture or spoil. This difference was manifested most strongly by the limited establishment of the seeded legume in the native topsoil. The other three materials were equally successful in establishing vigorous vegetative stands with favorable grass-legume composition.

Examination of the soil data does not reveal any probable plant growth constraint in the native topsoil with the exception of low levels of exchangeable magnesium in comparison to sandstone, mixture and spoil.

Since vegetation establishment on the sandstone and the mixture of sandstone and topsoil were similar, it appears that the sandstone had an ameliorative effect exceeding that which might occur from a dilution effect alone. The sandstone proved to be an effective liming material by reacting quickly with the acid topsoil to reduce exchangeable acidity and raise soil pH. It was superior to the agricultural limestone used in this study in that it supplied enough available magnesium to overcome an apparent deficiency of that nutrient in the native topsoil.

Conclusions

Although Kittanning coal overburden materials in many areas of Appalachia will produce extreme acidity when mined, the overburden in some areas produces very little, if any, acidity. Therefore, it is important to analyze the overburden before mining, and then develop specific overburden handling plans for those materials. The overburden in study #1 was more acidic than the topsoil, but in study #2 sandstone from the overburden was alkaline while the topsoil was acid. Acid-base account analyses predicted these results.

Development of a topsoiling program for reclamation of drastically disturbed land should be an important part of the planning stage of the operation. Considerations are site specific and vary widely depending on post mining land use, regulatory compliance, costs, and the quality and quantity of overburden materials which are available. It is also important to monitor the overburden ahead of mining, because overburden properties may change. Given a situation where an operator wishes to reclaim a site to pasture or hayland and has access to materials with soil properties similar to the native topsoil and crushed sandstone used in this study, blending of the two materials offers promise for this land use. Either of these materials by themselves possess properties which could potentially restrict rapid revegetation and site stabilization. The crushed sandstone, like many sandy soils, had a low moisture retention capacity, low cation exchange capacity, and may be susceptible to erosion on slopes. The native topsoil is quite acid and deficient in available magnesium. Blending of these materials eliminates or ameliorates all of the potential problems associated with the properties of the individual parent materials. This blend would still require an amendment of N-P-K fertilizer because both parent materials are deficient in these essential nutrients.

When formulating a blend of alkaline sandstone and acid topsoil to be used as a topsoil substitute for grazing and hayland post-mining land uses, some conditions must be satisfied. It is important that enough alkaline material be present to neutralize the soil acidity. In this study, good results were produced by a blend which contained twice the excess neutralization potential required to satisfy the soil test lime requirement. In situations dealing with unweathered geologic materials rather than topsoil, it is recommended that blending rates supply neutralizers in excess of the maximum potential acidity predicted by the acid-base account.

Another condition which must be satisfied by a topsoiling program is the achievement of a minimum thickness of cover. If, during the planning stage, estimates of the volume of available native topsoil are less than required to achieve the desirable minimum thickness over the post mining area, then blending of an additional appropriate material should be considered. A cover thickness of 15 cm should be considered as a minimum for all sites. Where potentially toxic (by acid-base accounting) materials are directly below the topsoil, greater thicknesses are recommended.

In summary, the use of topsoil substitutes, such as crushed alkaline sandstone, have the potential to help create superior minesoils. It should be stressed that for effective reclamation, a good topsoiling program needs to be followed promptly by a good revegetation program. Success in rapidly establishing a vigorous vegetative cover on suitable topsoil is an integral part of nearly all aspects of reclamation and water quality control.

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CURRENT RECLAMATION APPROACH AT THE SYNCRUDE OIL SANDS PLANT[1]

by

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Abstract. Syncrude Canada Ltd. is an oil sands surface mining and processing venture located at the Athabasca Oil Sands deposit in northeastern Alberta, Canada. An estimated 300 billion barrels of oil are considered recoverable from this deposit. The Alberta Government maintains that mined land be reclaimed to an acceptable end land use with a capability "equal to or better than" that which was present prior to mining. This paper presents an overview of Syncrude's current land reclamation approach. Prior to the mine overburden prestripping process, intensive sampling is conducted to assess the quality and volume of suitable reclamation materials present. These materials are then used to cap the tailings sand and the overburden disposal piles to depths of 70 cm and 100 cm, respectively. Locally grown indigenous tree seedlings are then planted on the capping materials. When reclamation is completed, the final land form, made up of recontoured undulating topography, with improved internal soil water drainage and soil properties, is expected to be at least equal to the pre-disturbed state in terms of ecological capability. The plant communities will be permanent, self-supporting and maintenance-free.

Additional Key Words: disturbed lands, afforestation, tailings sand, overburden, capping materials.

Introduction

The Athabasca oil sands of northeastern Alberta contains a vast accumulation of heavy viscous oil. The main body of the oil sands deposit covers between 31,000 and 34,000 square kilometres and contains over 600 billion barrels (1 barrel = 42 US gallons) of oil in place. Of this total, 300 billion barrels are considered recoverable; approximately 28% by surface mining technology and the remainder by other methods such as *in situ* thermal stimulation. Syncrude Canada Ltd. is the world's largest oil sands mining and processing venture, and is operating on the surface mineable portion of this oil sands deposit. It began production in 1978 and currently produces some 150,000 barrels of synthetic crude oil per day, approximately 10% of total Canadian oil consumption.

Syncrude's surface mining operations disrupt the environment. Plants are destroyed, soils are displaced and land forms are altered. Syncrude Canada Ltd. complies with requirements of the Alberta Land Surface Conservation and Reclamation Act to reclaim disturbed lands to acceptable end land uses either for forestry, wildlife, or recreation. Earlier reclamation methods used by Syncrude consisted of the amendment of overburden or tailings sand materials with 10 cm of clay and 15 cm of peat and incorporation of these amendments to a depth of 30 cm using agricultural implements. The lands were then fertilized and seeded with agronomic grasses and legumes followed by the planting of tree and shrub seedlings. However, this method has not proven cost effective relative to results achieved to date.

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This paper presents an overview of Syncrude's current approach to afforest lands disturbed by the oil sands mining operations. The two major land surfaces presently being reclaimed are overburden or oil sands disposal piles and tailings sand dykes.

Description of the Project Area

The Syncrude mining and processing plant is located approximately 420 kilometres northeast of Edmonton. The oil sands deposits on the Syncrude Leases underlies an average of 15 m of overburden. To gain access to the oil sands below, the overburden materials must be removed and disposed of.

Over the next 30 years of operation (1989 - 2018), Syncrude will feed 3.54 billion cu m of oil sands to the processing plant, and will move 1.77 billion cu m of overburden and reject materials to various disposal sites. Consequently, an estimated 14,000 hectares of land surface will be disturbed and then recreated for reclamation. In order to achieve reclamation standards, detailed documentation of the pre-mining land productivity coupled with sound reclamation planning and implementation are essential.

Reclamation Material Inventory

To evaluate and estimate the volume of materials *in situ* which are suitable plant growth media, detailed soil surveys are conducted in conjunction with Syncrude's ore-body core-hole drilling program. Soil samples are taken from drill cores 0 - 5 m deep at 1 m intervals and analyzed for physical and chemical characteristics. Soils are then rated as to their degree of suitability for plant growth. Suitability criteria are based on guidelines developed by the Alberta Soils Advisory Committee. The four rating classes are summarized as follows:

Good - None to slight soil limitations that affect use as a plant growth medium.

Fair - Moderate soil limitations that affect use, but which can be overcome by proper planning and good management.

Poor - Severe soil limitations that make use questionable. This does not mean that the soil cannot be used, but rather careful planning and very good management is required.

Unsuitable - Chemical and physical properties of the soil are so severe that reclamation would not be economically feasible or even possible.

Based on the rating results, a geological model is then drawn to depict the location of the various suitable soil types. Only materials falling in the good or fair categories which are located within 5 m of the surface are used for purposes of developing reclamation material balances. On the Syncrude Leases, the percentage of various geological units which are rated as suitable for plant growth are as follows:

. Holocene (Ho)	43%
. Pleistocene lacustrine (Pl)	30%
. Pleistocene fluvial (Pf)	63%
. Pleistocene glacial (Pg)	59%

The volume of suitable materials depends on the distribution of these geological units within the areas to be mined. Therefore, the quantity of *in situ* Holocene and Pleistocene materials which are suitable for reclamation use can be calculated by using the geological data projected over the area to be mined. However, the actual volume of recoverable materials in the mine areas may be reduced by factors such as:

- exploration activities;
- drainage ditches;
- excavation of road construction materials; and
- not all *in situ* materials can be mined cost-effectively especially those found in lower layers overlaid by poor quality materials.

Once the geological model is drawn, a more detailed investigation of the soil profile is necessary to supplement the preliminary information gathered through the core sampling program. This is done by digging soil pits with a backhoe, documenting the soil profile in a more detailed manner, and taking soil samples for further analysis. The areas with suitable reclamation materials are then delineated. These materials are selectively stripped and hauled directly to the reclamation sites for use as capping materials.

Capping and Site Preparation

Syncrude's current reclamation specifications call for tailings sands surfaces to be capped with 70 cm (± 20 cm) and saline/sodic or oil affected overburden surfaces with 100 cm (± 20 cm) of suitable capping materials. Stripping, hauling and capping are usually carried out in the winter months. The soil is spread to the desired depth and left until the following spring. In spring, the area is fertilized using fertilizer blends consisting of N, P, and K, and then the soil is immediately disked to form furrows along the slopes. The purposes of this procedure are to relieve soil compaction, control erosion, retain soil moisture and incorporate the fertilizers into the soil.

Afforestation

Syncrude's original methodology was to reclaim lands by initially establishing a dense ground cover of agronomic grasses and legumes to prevent soil erosion, followed by the planting of tree seedlings. This did not work well. The tree seedlings were suppressed by the heavy ground vegetation. As well, dense ground cover harbours rodents which gnaw on the bark of the young seedlings. The end result is seedling mortality. Syncrude is now exploring the feasibility of planting trees directly onto newly prepared sites with no vegetative cover, or a minimum vegetative cover made up of native herbaceous species.

Tree species are selected in accordance with guidelines set by the Alberta Forest Service. Indigenous species are preferred as they are better adapted to the harsh local climate. Local seed sources of jack pine (*Pinus banksiana* Lamb.), white spruce [*Picea glauca* (Moench) Voss], red osier dogwood (*Cornus stolonifera* Michx.) and trembling aspen (*Populus tremuloides* Michx.) are used to grow seedlings in two fiberglass greenhouses located on the Syncrude site. Some field test plots are being evaluated for Siberian larch (*Larix sibirica* Ledeb.) and hybrid poplars (*Populus x Populus* species) - two non-native species relatively cold hardy and adaptable to the local climate.

Syncrude opted to grow its own seedlings primarily to achieve better seedling quality and flexibility of scheduling than was obtainable from commercial growers. Good stock quality is assured by keeping seedlings in their original containers until they are ready for planting, thereby eliminating damages resulting from repackaging seedlings and improper handling during transport and storage.

Field research experiments showed that large planting stock was preferable for planting on the Syncrude land reclamation sites. Thus, Syncrude now grows its planting stock in 750 ml containers. The two greenhouses are capable of producing 62,000 seedlings of this size per crop and two crops per growing season. The first crop of the year is normally started in March and moved to a shadehouse in May for further growth and development. The second crop is sown in June and moved to the shadehouse in August. Seedlings are kept in the shadehouse anywhere from one to three years depending on the rate of growth of the species as well as the availability of land for reclamation. Seedlings which are not planted right away are overwintered in the shadehouse except for the more cold sensitive species, such as the jack pine, which are overwintered in a double-poly house.

With the annual two crop production, Syncrude is currently equipped to reclaim and afforest 50 hectares of land annually. Land availability is projected two years in advance in order to plan seedling production. Species to be planted are matched with the anticipated soil moisture availability on the reclamation sites, rather than soil type, because the soil types formed after capping are very heterogeneous. For example, jack pine, a drought tolerant species, is planted on the drier south-facing slopes. Planting density is 2,000 stems per hectare made up of half conifer and half deciduous species. Tree species are planted in alternate rows 2.5 m apart and 2.0 m between seedlings within a row.

Planting is done either in the Spring (May - June) or in the Fall (August - September). Planted areas are monitored annually for seedling survival and growth, ground cover development and soil chemical and physical properties. Any changes or trends are documented and results are then compared with set standards to update reclamation progress.

Summary

Construction and operation of the Syncrude Oil Sands Plant will eventually disturb a total of over 14,000 hectares of land surface. The disturbance began in 1973 with localized clearing, and will continue throughout the life of the project. Syncrude began reclaiming disturbed lands in 1976 with the objective of progressively establishing self-perpetuating plant communities which meet the objectives outlined in the Syncrude Development and Reclamation Plan approved by the Alberta Government.

The post-mining areas, overburden disposal piles, tailings sand dykes, and tailings sand storage areas offer a unique reclamation challenge. Syncrude intends to reclaim these areas to a state usable for forestry, wildlife and recreation. The capability of the land surface will be re-established via placement of a minimum of 70 cm of suitable capping materials using the criteria supplied by the Alberta Soils Advisory Committee. Reclamation materials are being selectively mined using mobile equipment prior to overburden removal and then hauled directly for placement upon reclamation sites. The new land surfaces will be contoured to form gentle slopes and allow good drainage. After disking and fertilizer application, the land will be afforested in order to speed up the rate of plant succession to meet Syncrude's long-term reclamation objectives. The required seedlings are produced by Syncrude in on-site greenhouses using seed collected locally. Native species are being used to improve the rate of success and to ensure that the 'man-made' plant communities blend in with the surrounding vegetation. The final landscape is anticipated to be dominated by a spruce-aspen forest type with jack pine predominantly on the exposed southern and western slopes.

COAL MINE SOIL AND OVERBURDEN SURVEYS AND RECLAMATION PLANNING[1]

by

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Abstract. The Highvale Mine, located in Central Alberta approximately 65 km west of Edmonton, is one of several large coal strip mines presently operated in agricultural areas of Alberta. Government guidelines require that mined land be returned to a capability equivalent to pre-mine conditions. Detailed soil and overburden surveys were conducted at the Highvale Mine in 1984-85 for areas to be mined in the 25 year period, 1986 through 2011. Soil survey information collected from approximately 1500 field inspections was used to: document the distribution, morphology and chemical/physical properties of soils; determine land capability for agriculture (CLI); determine soil suitability for reclamation; and provide a data base for surface soils. A total of 448 drillholes were completed to determine overburden thickness and to collect samples. Chemical and physical data from drillhole samples were used to describe properties of principal overburden units and to rate overburden materials for reclamation suitability. Information from the soil and overburden programs was integrated to optimize materials handling efficiency and achieve reclamation objectives.

Additional Key Words: subsoil, soil capability, soil suitability, reclamation planning, geographic information system.

Introduction

Strip mining of coal involves the removal of soil and overburden which lies above the coal and then extracting the exposed coal. Mining and reclamation are now generally more or less integrated. Topsoil, and often also subsoil, are removed prior to mining with scrapers. These materials are then stockpiled for subsequent use or, if possible, placed directly on levelled mined land.

Reclamation problems result from the nature of the overburden materials and the method of mining. The overburden which occurs over the coal is often soft bedrock of later Cretaceous age with chemical and physical characteristics adverse to plant growth. Strip mining with draglines results in material from the surface being placed in the bottom of the pit and the deeper material ends up at the surface. The sequence of strata are therefore reversed, with the undesirable overburden at the surface. This material is often extremely sodic with a very high sodium content and has a high proportion of swelling clays (Schori, 1985).

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[1] Paper presented at the conference Reclamation, A Global Perspective, held in Calgary, Alberta, Canada August 27-31, 1989.

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In Alberta, provincial government policy requires that "... disturbed land will be returned wherever possible to a state that will support plant or animal life or be otherwise productively useful to man, at least to the degree it was before it was disturbed" (Coal Development Policy 1976). Alberta Government Regulations and Guidelines also require that appropriate soil salvage and replacement be carried out so that reclaimed land will have a land capability equal to that which existed prior to mining. In order to meet these government requirements, appropriate data regarding the nature and extent of soils and overburden in the pre- and post-mining environments is required.

Surface coal mining at Highvale, about 65 km west of Edmonton, began in 1971. To date, coal has been removed from four pits within the Highvale Mine permit area. The pits are located along the south side of Lake Wabamum in a 16 km long, 6560 ha band from east to west (Figure 1). Mining in each pit commenced near the lake and has proceeded southward over time. TransAlta Utilities Corporation's Highvale Mine supplies about 12 million tonnes of coal per year to the Sundance and Keephills thermal power plants,

Reclamation experience over the past few years at Highvale indicated that some reclaimed areas do not have good soil tilth. TransAlta therefore reviewed the soil suitability for reclamation criteria and recommended modifications.

The following discussion outlines the generation and interpretation of soil data for mine planning and reclamation at the Highvale Mine.

Methods

Reclamation planning for subsoil handling has evolved as a multidisciplinary task involving pedologists, geologists and mining engineers. Standard pedology and surficial geology survey techniques and laboratory analyses were conducted. Soil and overburden information was then integrated to refine suitable subsoil distribution patterns, spatially and vertically.

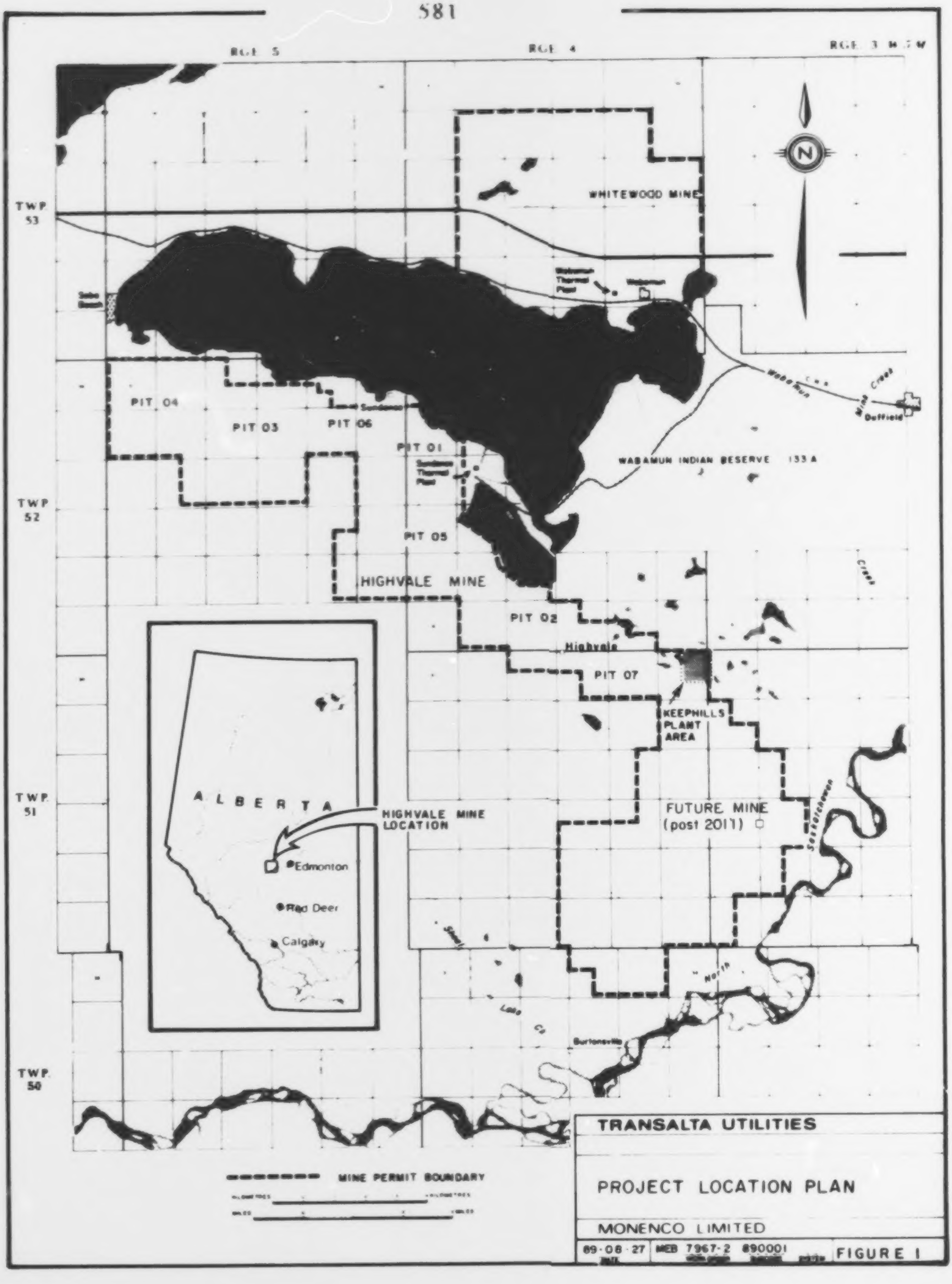
Subsoil handling was optimized using mine plans combined with information on soil volumes (annual replacement requirements and availability) from the baseline soil survey map and end land use plans.

This section outlines the methods used in conducting the soil survey, overburden survey, laboratory analyses (soils and overburden), suitability rating, survey data integration and materials handling optimization.

Surveys

Soil Survey. The soil survey was conducted in 1985 (Monenco Ltd., 1986). Pits 02, 03 and 04 were surveyed at survey intensity level 1 (SIL 1), with one field inspection per 10 ha. Pits 05 and 06 were surveyed at SIL 2, with one field inspection per 10 ha. Soil maps were produced at a scale of 1:10,000.

Approximately 1,500 field inspections were made. These inspections included: 37 soil pits described in detail and sampled; 650 inspections included exposing A and B soil horizons with a shovel, to determine soil structure, and hand augering to one metre; and approximately 800 inspection sites were hand augered to the C horizon (parent material) or to 1 m. Approximately 10% of the inspection sites were sampled. All the site locations were recorded.


RGE 5
RGE 4
RGE 3 W.5 M
TWP 53
TWP 52
TWP 51
TWP 50
WHITEWOOD MINE
Wabamun Thermal Plant
Wabamun
Seba Beach
PIT 04
PIT 03
PIT 06
Sundance
PIT 01
Sundance Thermal Plant
Wabamun Creek
Mink Creek
Duffield
WABAMUN INDIAN RESERVE 133 A
PIT 05
HIGHVALE MINE
PIT 02
Highvale
PIT 07
KEEPHILLS PLANT AREA
FUTURE MINE (post 2011)
Saskatchewan
North
Burtonsville
ALBERTA
HIGHVALE MINE LOCATION
Edmonton
Red Deer
Calgary
MINE PERMIT BOUNDARY
KILOMETRES
MILES
N

TRANSALTA UTILITIES

PROJECT LOCATION PLAN

MONENCO LIMITED

89-08-27 MEB 7967-2 890001 FIGURE 1

Field data sheets were completed for each site.

Soils were classified according to the Canadian System of Soil Classification (Canadian Soil Survey Committee 1978). Soils were described as per the Canada Soil Information System Manual (Day, 1983). Twenty-six soil series were described and named according to the Alberta soil series conventions.

The soils were rated for agricultural capability according to Canada Land Inventory Guidelines (Brocke, 1977). The system groups mineral soils into seven classes according to their capability for agricultural use. Classes 1 to 3 are capable of sustained production of common cultivated crops; class 4 is considered marginal for cultivation; Class 5 is capable for only permanent pasture or hay; Class 6 is capable for native grazing and Class 7 has no capability for agricultural use. Organic soils are not rated.

Overburden Survey. An overburden drilling and sampling program was conducted during the period 1984 to 1986 in Pits 02 through 07. The program was conducted at two levels of intensity: detailed - 1 drillhole per 4 ha (200 m grid); and reconnaissance - 1 drillhole per 64 ha (800 m grid). Table 1 presents a summary of the drilling and sampling intensity by individual pit. The detailed drilling was required in areas currently under development. The reconnaissance was carried out in areas to be mined in future (i.e. not for at least 5 years).

A total of 448 drillholes were completed. Sixty-two drillholes penetrated coal and were drilled by a reverse circulation drill rig. An auger rig drilled the remaining 386 drillholes to auger refusal. A total of 4311 samples were examined (stratigraphy, lithology, thickness, color, texture, plasticity, consistence)and 1770 samples were collected for laboratory analyses.

TABLE 1

Summary of Soil and Overburden Inspections and Sampling

			Overburden	Soil	
Mine Pit Number	Area (ha)	Inspection Density	Number of Drillholes	Number of Sites Inspected	Number of Sites Sampled
Pit 02	506	detail	122	313	38
Pit 03	832	detail	143	425	50
Pit 04	809	detail	141	637	69
Pit 05	308	reconnais.	13	50	14
Pit 06	209	reconnais.	18	59	16
Pit 07	N/R	reconnais.	11	4	4
Total	2664		448	1478	191
Number of Samples Analyzed			1770		433

N/R - Not Reported (area to be mined after 2011)

Geophysical logging of the reverse circulation drillholes was carried out to aid correlation of auger and reverse circulation drillholes, in order to prepare overburden cross-sections. The logging package included natural gamma ray, long-spaced side wall density, bed resolution density, caliper, dual-spaced neutron and focussed electric.

Laboratory Analyses

An extensive analytical program was conducted by Monenco Analytical Laboratories to chemically and physically characterize the soil and overburden materials. Methods of analysis are presented in Table 2.

A quality control program, using standard check samples from the Highvale area, was also conducted by the laboratory.

Soil Analyses. Chemical and physical analyses were conducted on 433 samples.

Overburden Analyses. Samples (1770) were analyzed to determine chemical and physical parameters of the 10 major stratigraphic units. The parameters included: grain size (% sand, silt and clay); pH; EC; SAR; % ESP; CEC; and saturation %.

Reclamation Suitability Ratings

Both the subsoil and overburden materials were rated for reclamation suitability. Topsoil was not rated as all topsoil is considered suitable for salvage and replacement.

Subsoil Suitability Ratings. Subsoil suitability criteria, shown in Table 3, are as per Alberta Soils Advisory Committee (1981) with some modifications. Local reclamation experience showed that modifications were necessary to reflect the combined effect of marginally adverse physical and chemical characteristics.

TABLE 2

Laboratory Analysis

Parameter	Method[a]	
Physical		
grain size (sand, silt, clay)	(3 point hydrometer)	2.12
saturation %		3.21
pH	(of extract)	3.21
electrical conductivity	(of extract)	3.21
organic carbon[b]	(mod. Walkley-Black)	3.613
Chemical		
soluble cations, SAR	(Ca, Mg, Na, K)	3.26
cation exchange capacity		3.321B/3.34
exchangeable cations[c]	(Ca, Mg, Na, K)	3.321A

[a] reference: McKeague, 1978.

[b] topsoil (Ap, Ah, Ahe) horizons of detailed pits only.

[c] subsoil (B) horizons - where SAR is greater than 8 and/or EC is greater than 2; and from selected B horizons with columnar or prismatic structure.

Four categories of subsoil suitability were developed (TransAlta Utilities Corporation, 1986).

Category 1 - Solonetzic Soils and fine textured Gleysolic Soils (no suitable subsoil). The B and C subsoil horizons of the Solonetzic soils are unsuitable for reclamation due to heavy clay textures, columnar to blocky structure, very hard consistence when dry, and high SAR and ESP values. The B and C subsoil horizons of the Gleysolic soils are unsuitable due to clay and heavy clay textures and very sticky consistence.

Category 2 - Fine Textured Luvisolic Soils (shallow suitable). The B horizons are suitable subsoil for reclamation. They are non-sodic, with silty clay to clay texture, blocky structure and sticky (wet) to hard (dry) consistence. These properties are expected to provide manageable subsoil conditions upon replacement. These soils have approximately 0.4 m of suitable subsoil below the topsoil. The C material has clay to heavy clay texture, massive structure and is very sticky and very plastic when wet or very hard when dry. Although non-sodic and non-saline, the C horizons

TABLE 3

Highvale Mine
Soil Suitability Criteria for Reclamation

Criterion	Unsuitable	Poor
pH	<4.5 or >8.5	8.0 - 8.5
SAR	>12	8 - 12
ESP	>15	10 - 15
EC mS/cm	>10	5 - 10
Saturation %	>120	80 - 120
Clay %	>60	40 - 60
Consistence[a]	Extremely Hard When Dry or Very Firm When Moist or Very Sticky and Very Plastic When Wet	Very Hard When Dry or Firm When Moist or Sticky and Plastic When Wet

If two suitability criteria in the following combinations are "poor" then a soil is also rated unsuitable.

Clay and Consistence
or Clay and SAR
or Clay and ESP
or Consistence and SAR
or Consistence and ESP

[a] Consistence as defined by CSSC, 1978.

Source: TransAlta Utilities Corporation. 1986. Highvale Mine - 1985 Development and Reclamation Plan are unsuitable due to very high clay content or a combination of clay and poor consistence.

Category 3 - Medium to Coarse Textured Luvisolic Soils (deep suitable). The B horizons are suitable subsoil due to sandy clay loam to silty clay loam textures, lack of sodicity and salinity and friable to firm consistence. The C horizons are also suitable as subsoil due to loamy sand to silty clay textures, massive to single grain structure, friable to firm consistence and lack of sodicity or salinity. These soils have at least 1.5 m of suitable subsoil.

Category 4 - Organic Soils (not rated). Organic soils have not been rated for reclamation suitability. These soils may be used as required as soil amendments.

Categories 2 and 3 have subsequently been refined to reflect differences in parent material thickness see section on Survey Data Integration).

Overburden Suitability Ratings. The same reclamation suitability rating system used for subsoils was used for overburden (Table 3). Each stratigraphic layer was rated for suitability.

Geographic Information System (GIS)

In order to handle the numerous possible permutations when summarizing information contained on the soil map a GIS was used. The system used was microcomputer based, using an IBM compatible microcomputer equipped with a 30Mb hard drive and color monitor (16 color). The GIS software is produced by TYDAC Technologies and is available under the name SPANS. The software allows for multiple (14) overlays of maps of various themes and produces a "unique conditions report" from these multiple overlays. The report can be imported into a spreadsheet environment where numerous sorts and data analyses are performed.

Survey Data Integration

Subsequent to the completion of the overburden and soil surveys it was evident that a method of integrating subsoil information from the two programs was necessary for reclamation and materials handling planning.

The soil survey information was applicable to the surface 1 to 1.5 m. The overburden programs describe the material below 1.5 m to coal. However, at many overburden dill holes soil material was also described and sampled as shallow as 0.8 m. The overlap of soils and overburden data for the 0.8 and 1.5 m depth required integration of the data. Correlation of soil parent material (C horizon) and overburden stratigraphic units required detailed review of field data and logs from both surveys (Monenco Ltd., 1987).

Soil Map Units and Stratigraphic Divisions. Cross sections, at 400 m intervals, were prepared for each pit. Soil polygon and inspection point data were compared to the information for the surface 1.5 m at each overburden drillhole. Direct comparisons were made between the nomenclature conventions used in the two programs. From these comparisons it was possible to develop a relationship between the soil parent materials and corresponding overburden stratigraphic layers. The combined information on subsoil suitability was used to determine the location and depth of suitable material for reclamation.

The integration of overburden soil information with soil survey information allowed refinement of the depths of suitable subsoil material for soils in Suitability Category 2 (shallow) and, particularly, Category 3 (deep). The Category 3 soils were defined as suitable to 1.5 m in the soil survey, but the overburden information confirmed the actual depths, which ranged from approximately 2 m to 7 m.

Suitability Maps. Three types of subsoil suitability depth maps were prepared. First, a computer generated isopach map based on overburden drillhole data. Second, a soil polygon map (ie. soil survey map) with portions of isopachs (based on overburden information) within polygons as appropriate. Third, a soil polygon map with the average depth of suitable subsoil indicated. The third map is used for short and long term mine planning. The original soil survey map comprised 26 soil units. The soil polygon map, with average suitable subsoil depths has been simplified to 11 map units with suitable subsoil thickness ranging from 0 to approximately 7 m.

Reclamation Targets

Agricultural Capability. Agricultural capability of the land prior to mining dictates reclamation targets since the capability of the reclaimed land is to be equivalent to that which existed prior to mining. The best agricultural land in the Highvale area is Class 3. There is no Class 1 and 2 land due to climate limitations. Agricultural capability (based on total for all pits) is: 22% Class 3; 36% Class 4; 33% Class 5; and 5% Class 6. The percentage of Class 3 land is similar in all Pits.

Subsoil Requirements. Subsoil is replaced on all levelled minespoil. Subsoil is replaced to a depth of 1.5 m over a total area the same size as the total Class 3 land prior to mining (i.e. 22%). All other area receive 0.35 m of subsoil.

Materials Handling Optimization

The subsoil suitability depth maps form the basis for subsoil salvage optimization studies. The objective of the subsoil optimization plan is to schedule the salvage and replacement of suitable subsoil taking into consideration the following:

1) Minimize subsoil haul distances.

2) Minimize double handling and stockpiling of subsoil by directly replacing subsoil when it is salvaged.

3) Confine the area of deep replacement (Class 3 agricultural capability) to one specific block.

4) Where possible, use primarily deep subsoils in the salvage operation

5) Utilize future pre-stripping truck/shovel operations advantageously to salvage subsoil.

Deep Subsoil Replacement. Deep (1.5 m) subsoil will generally be replaced in one block in each pit whenever possible. In order to optimize the placement of the deep subsoil block a number of thematic maps were examined, including maps showing the area of land made available for replacement on an annual basis as well as post-mine topography. The deep replacement block was optimally sited using the information generated by SPANS combined with criteria of: 1) maximum direct replacement; 2) minimum haul distance and 3) placement on near level or level areas.

Subsoil Salvage. Subsoil is salvaged annual immediately prior to mining. Salvage occurs only on an as needed basis. Direct replacement is the preferred method of subsoil salvage.

Volumes of suitable subsoil, available on an annual basis, were determined with SPANS by overlying the annual salvage mine plan on the suitable subsoil thickness map. By first determining the available volumes of suitable subsoil, adjustments in replacement requirements were made (by shifting the location of the deep replacement block) to take advantage of potential surpluses (maximize direct hauls) and avoid potential deficits (requiring stockpiling or longer hauls from more distance sources).

Results and Discussion

The primary result of combining soil survey and overburden survey information has been to refine the location (horizontal and vertical extent) and estimate of reserves of suitable subsoil material in each of the six mine pits. By refining the soil map information to include overburden thickness data, more accurate volume estimates were possible then would be made by using soil or overburden information alone.

By determining subsoil availability and replacement requirements early in the life of the mine it has become possible to selectivity handle suitable subsoil materials.

Mine planning exercies involve numerous iterations of alternative mine cut plans, resulting from changes in production scheduling or other factors. In the past each change in the mine plan resulted in time consuming and tedious recalculation of impacated areas (ie. recalculation of areas and volumes of disturbed soils). By digitizing the soil polygons and entering this information into a geographic information system with large and flexible attribute files and an excellent reporting system (unique conditions report) the type of information required can be generated quickly allowing for rapid comparisons of alternative mine plans. The GIS used allowed for easy importing of individual mine block/pit boundaries, another essential component in the data handling.

Alternative Uses of GIS Enhanced Data. To date we have used the GIS as a tool primarily to keep an exact aerial accounting of soil data on a digitized soil map base, combined with detailed mine plan information. This application is particularily useful for medium and long term planning.

The GIS is also extremely powerful tool in manipulating and presenting site specific data from the soil and overburden databases. For example, instead of using averages soil thickness, worked out for the entire mine area, specific information from individual drillholes or soil inspections can be reviewed or presented. This readily accessible data allows checking of average depths of suitable subsoil for specific map polygons and identification of areas where data may be difficient. For example, average depths for certain subsoils may be misleading if depths are highly variable (i.e. large standard deviation relative to the mean).

Summary

Computer databases and a GIS are only tools to enhance the basic data collected in the field. The individual field programs must be designed to collect sufficiently detailed information on the characteristics and extent of individual soils and overburden types.

Information from soil surveys and overburden surveys must be integrated to ensure maximum benefit of this information for mine planning and reclamation planning.

Optimizing the movement of large soil volumes is an essential element in mine reclamation planning. By combining the information from the integration study (soil/overburden) with alternate mine development plans, optimal soil handling plans can be developed. The use of a GIS in soil handling optimization studies significantly reduces the amount of the tedious and time consuming work. Optimization of salvage and replacement of suitable reclamation materials can significantly reduce the cost of materials handling.

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SPATIAL VARIABILITY IN THE CHEMICAL AND PHYSICAL PROPERTIES OF REGRADED MINE SPOIL[1]

by

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Abstract The variability in the chemical and physical properties of regraded mine spoil was measured at four locations in western North Dakota. The ultimate objective of this study is to predict regraded surface properties from core data from the original overburden. The samples were taken from an expanding square pattern so the variability in a small area could be compared to the variability in a large area. The size of the area sampled ranged from 9 sq. m to 55 ha. Spoil properties measured included pH, electrical conductivity, soluble Ca, Mg and Na, sodium adsorption ratio and percent sand, silt and clay. Variability in soil properties as measured by the coefficient of variation in the smallest area was 30-70% of that in the largest area for most parameters at three mines. Difficulties were encountered in matching the premine overburden with the regraded spoil properties because the degree of surface grading following mining was not predictable. Sampling to a depth of 1.2 m in 0.3 m increments did not significantly improve the information available on the variability of spoil properties compared to the surface 0.3 m alone.

Additional Key Words: reclamation, overburden, chemical properties, physical properties, premine.

Introduction

The amount of topsoil and subsoil necessary to reclaim mined land in the northern Great Plains is dependent on the properties of the spoil material. In a subsoil wedge experiment in which the combined topsoil - subsoil thickness was increased from 0 to 2.1 m over highly sodic spoil, highest yields of all crops occurred when about 0.20 m of topsoil was placed over 0.55 to 1.10 m of subsoil (Power et al., 1981). The depth of soil required for maximum production on 15 wedge plots in Wyoming, Montana, and North Dakota was dependent on spoil characteristics (Barth and Martin, 1984). Maximum production was achieved on these plots when replaced soil depths were 0.71 m on sodic spoil, 0 m on soil-like spoil and 0.50 m on spoil lacking distinguishing traits such as sodicity. Spoil materials can be inherently deficient in available nutrients, especially P and N (Bauer et al., 1965, 1966). Merrill et al. (1985) reported that the low hydraulic conductivity of sodic minespoil (sodium adsorption ratio

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(SAR) = 30) was the dominant factor limiting plant growth. In a study using trenches which simulated reclamation with various types of spoil material at least 0.69 m of silt loam topsoil was necessary to produce maximum yields over sandy loam spoil (Halvorson et al., 1986). On moderately sodic spoil yields of corn silage and wheat grain were significantly higher on 0.15, 0.30 and 0.60 m of topsoil compared to 0.05 m (Halvorson et al., 1987). The clay loam spoil in this study was not as drought prone as the sandy loam topsoil and therefore, as the thickness of topsoil increased, the ability of the profile to continuously supply water to the growing crop decreased.

The results of these and other experiments have been summarized by Doll et al. (1984). They also drew up recommendations for topsoil depth replacement based on spoil properties in the northern Great Plains. These spoil properties are not uniform in a permit area or a tract of reclaimed land. It is therefore, important to understand the variability in spoil properties and how this affects the reclamation of a given tract of mined land. It would also be useful to predict this variability in spoil material from the original overburden bore hole data. The objectives of this research were therefore; (1) to determine the variability of regraded spoil; (2) determine the depth of sampling necessary to characterize this variability, and (3) predict the regraded spoil properties from the original premine bore hole data.

Methods and Materials

Four sites were selected for study, one each at the Indianhead, Glenharold, Falkirk and South Beulah Mines in North Dakota. The sites were located on regraded spoil which was at or near final grade. Sampling was done using an expanding square technique. This sampling scheme has also been called a systematic radial sampling scheme (Wilding, 1985). An area of 3 x 3 m was subdivided into 9 equal squares and the center of each square was sampled to a depth of 1.2 m in 0.3 m increments. An area of 9 x 9 m was subdivided into 9 equal squares using the original 3 x 3 m area as the center square. The center of each of the new expanded squares was sampled to a depth of 1.2 m. The square was expanded similarly a total of five times to give six sampling areas of different sizes. The largest expansion sampled (#6) had a total area of 55 ha.

Clay percentage was determined using the pipette method (Day, 1965). A glass electrode was used to measure pH (Peech, 1965). Soluble salts, (electrical conductivity (EC) and saturation percentage were determined on saturation extracts (Bower and Wilcox, 1965) and soluble Ca, Mg, and Na concentrations were determined quantitatively using atomic absorption spectrophotometry and were used to calculate SAR values.

The standard deviation and coefficient of variation were calculated for each expansion at each site. Analysis of variance was used to determine significant differences between sampling depths for each square expansion.

Results and Discussion

Mean values for all parameters for each expansion at each site generally did not change very much as the size of the sample area increased (Table 1). An exception was the SAR values at the Indianhead Mine which increased from 10 in the smallest area (expansion 1) to 19 and 17 in expansions 5 and 6, respectively. The SAR in the center was lower than most of the surrounding sample area at this site.

Table 1. The mean, standard deviation (STD) and coefficient of variation (CV) of the sodium adsorption ratio (SAR), saturation percentage (SP), electrical conductivity (EC), and % clay content from a site at each of four mines in North Dakota.

Mine	Expansion	Mean	STD	CV	Mean	STD	CV
			SAR			SP	
South Beulah	1	16	4	23	90	8	8
	2	16	2	14	91	7	8
	3	16	3	18	91	9	10
	4	17	6	34	87	12	14
	5	14	3	20	93	13	14
	6	12	8	65	91	18	20
Glenharold	1	43	5	12	154	19	12
	2	44	3	7	151	13	9
	3	41	6	14	147	19	13
	4	41	5	13	140	17	12
	5	41	5	13	137	16	12
	6	40	5	13	141	15	11
Indianhead	1	10	1	11	67	5	7
	2	10	1	9	69	5	7
	3	11	3	25	76	12	16
	4	17	6	34	100	24	24
	5	19	8	42	97	25	26
	6	17	9	49	96	22	22
Falkirk	1	4.9	1.6	32	80	6	7
	2	5.4	1.5	27	78	5	6
	3	3.5	1.4	41	78	5	7
	4	6.2	2.6	41	78	8	11
	5	3.6	2.3	63	77	10	13
	6	5.4	3.8	70	74	10	13
			EC (dS/m)			% Clay	
South Beulah	1	6.9	1.0	14	39	2	5
	2	6.8	0.8	12	40	3	8
	3	6.7	1.1	16	39	3	8
	4	6.7	1.1	16	38	4	11
	5	6.9	1.2	17	39	5	13
	6	5.9	1.6	26	40	7	17
Glenharold	1	2.1	1.4	66	33	7	22
	2	2.0	0.7	36	33	6	20
	3	2.7	1.8	66	33	6	19
	4	2.8	1.3	47	34	6	18
	5	2.8	1.2	41	33	5	15
	6	2.6	0.7	29	31	6	20
Indianhead	1	4.8	0.6	13	26	3	12
	2	4.7	0.5	11	26	3	10
	3	4.5	0.8	18	28	4	15
	4	4.6	1.3	29	34	8	23
	5	4.5	1.3	29	33	7	21
	6	4.4	1.4	31	32	5	16
Falkirk	1	4.4	0.5	12	33	4	12
	2	4.4	0.6	13	33	4	11
	3	4.3	0.2	4	37	6	15
	4	4.2	1.2	28	32	14	13
	5	4.2	0.8	20	34	8	24
	6	3.6	1.0	29	29	8	26

For all parameters at all sites except the Glenharold site the coefficient of variation (CV) increased as the sampling area (expansion) increased. For example, at the South Beulah Mine the CV increased from 23% in expansion 1 to 65% in expansion 6. This means that about 35% of the variability in SAR from the largest expansion could be found in an area of $9m^2$. For most of the parameters the CV of expansion 1 was 30-70% of expansion 6. Therefore, a significant portion of the variability in the larger area could be found in a rather small area of regraded spoil. This seems to indicate that considerable mixing of the overburden material had occurred during the mining process.

At the Glenharold Mine the CV values for all parameters did not increase as the size of the area sampled increased and tended to decrease for EC. These data would indicate that spoil material at this site had been thoroughly mixed. Much of the mixing probably occurred in the final grading process. Material from a topographic high was spread over much of the area so that the properties of the spoil in a small area became the properties of the spoil in a much larger area. As discussed later, this extensive regrading of the spoil material causes problems in matching the regraded spoil properties with those of the original overburden.

Analysis of variance was run to determine if significant differences occurred between the sampling increments of 0.3 m in the regraded spoil. The level of significance for the Glenharold site is given in Table 2 as an example. Results were similar for the other three sites. In general, there were very few significant differences between the different sampling depths. Where significant differences did occur, they were usually in the four smallest sampling areas (expansions). These data indicate that very little additional information on the variability of regraded spoil properties can be obtained by sampling to a depth of 1.2 m rather than just sampling the surface 0.3 m.

The characteristics of the regraded spoil at the Falkirk Mine were compared with the data from eight original bore holes which would be expected to influence the properties of the regraded spoil. The percent frequency of SAR at values from 0-19 indicates a fairly close match between the regraded spoil and the original overburden properties (Table 3). Values for EC in the original overburden were concentrated in the range of 1-6 dS/m with 35% having a value of 1 ± 0.5 dS/m. In the regraded spoil EC values had a wider range of 1-9 dS/m and the highest percentage of values (17%) at 3 ± 0.5 dS/m. Some EC values were as high as 19 dS/m in the regraded spoil. Based on the frequency tables for EC the match between regraded spoil and the original overburden was poor.

The % clay in the original overburden was concentrated in the range of 20-45% with 58% of the samples having clay contents of 25-30%. The regraded spoil on the other hand was mainly in the 30-65% range with 71% of the samples having clay contents of 35 to 45%. The values for % clay in the regraded spoil and in the original overburden do not match and would suggest two different populations. The clay % in the original overburden samples did not exceed 45 while 19% of the samples in the regraded spoil exceeded this value. The only original overburden sampling point which had clay contents above 45% was located several hundred yards south of the regraded spoil sampling area. Since the pit was running east-west and the mining was proceeding northward this original

Table 2. Level of significance at the Glenharold site for differences in sampling depth for each expansion size.

Expansion	SAR	SP	EC	% Clay
	Level of Significance			
1	0.179	0.280	0.305	0.082
2	0.814	0.655	0.980	0.985
3	0.042*	0.370	0.375	0.961
4	0.653	0.073	0.262	0.586
5	0.099	0.037*	0.132	0.800
6	0.303	0.999	0.666	0.457

* A value of 0.05 or less indicates significant differences do occur.

Table 3. Percent frequency distribution for SAR, EC and percent clay in 8 original overburden bore holes (OB) and in regraded spoil (RS) from the Falkirk Mine.

SAR	OB	RS	EC	OB	RS	Clay	OB	RS
	---%---		dS/M	---%---			--------%-------	
0	2	0	0	4	0	0	0	2
1	28	11	1	35	11	5	0	0
2	19	8	2	12	8	10	0	0
3	12	17	3	13	17	15	0	0
4	9	11	4	12	11	20	8	2
5	2	11	5	12	11	25	33	0
6	3	8	6	9	8	30	25	9
7	2	11	7	3	11	35	19	18
8	3	3	8		3	40	8	39
9	3	11	9		11	45	3	14
10	3	0	10		0	50		9
11	4	3	11		3	55		2
12	6	3	12		3	60		4
13	6	0	13			65		4
14			14					
15			15					
16			16					
17			17					
18			18					
19		3	19		3			

sampling point would not normally have influenced the regraded spoil properties. In checking with the Falkirk Mining Company personnel, it was learned that this area following mining was a topographic high and had been smoothed down in the final regrading process. The material from this one spot had therefore, been spread over a much larger area including the sampling area on regraded spoil. The properties of the entire regraded spoil area on the surface were characteristic of that one site several hundred yards to the south.

Because the amount of regrading on the source of the added material in the final regrading process cannot usually be predicted before mining, it is nearly impossible to predict regraded spoil properties from original overburden bore hole data. Research is currently underway to determine whether original overburden data can predict "rough" graded spoil properties, that is, before any extensive recontouring or movement of materials has occurred. Such a predictive capacity could be useful in planning final regrade to obtain optimum surface physical and chemical properties for reclamation.

Conclusions

A sampling scheme known as an expanding square sampling scheme or a systematic radial sampling scheme was used to compare spoil variability from a small area with that in a large area. At the Indianhead, Falkirk and South Beulah mine sites the CV's of the measured parameters in the smallest sampling areas were 30-70% of the CV's in the largest sampling areas. At the Glenharold mine extensive regrading produced CV's which were uniform and independent of sampling size area.

Analysis of variance indicated that no additional information on the variability of spoil properties was gained by sampling down to 1.2 m in 0.3 m increments than from the surface 0.3 m alone.

A comparison of the properties of regraded spoil with original overburden data indicated difficulties in matching the two. In the examples used at one mine SAR values in the regraded spoil matched fairly well with the original overburden data, but the EC and especially the % clay values did not match and were considered to be from different populations. The reason for the poor match was due to the extensive recontouring and movement of spoil material from one area to another during final grading. This process makes it nearly impossible to predict regraded spoil properties from original overburden bore hole data.

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WEATHERING OF SIDERITE ($FeCO_3$) FROM LIGNITE OVERBURDEN[1]

by

N. M. Frisbee[2] and L. R. Hossner[3]

Abstract. Acid/base accounting of minesoils and overburden can have substantial errors using current analytical procedures. There is a correlation between the presence of siderite ($FeCO_3$) and errors in determining the neutralization potential and potential acidity of overburden material. The effects of CO_2, O_2, and air on siderite weathering were measured. Unoxidized siderite blocks were placed in containers with H_2SO_4 or potassium hydrogen phthalate (KHP), both at pH 3.0. Carbon dioxide, O_2, or air was bubbled through the solutions. The solutions were changed regularly and aliquots were analyzed by atomic absorption for Fe. Unoxidized siderite and $CaCO_3$ were used in pH-stat titrations to determine reaction rates at pH 3.0. Iron release from siderite was influenced by gaseous environment and decreased in the order: $CO_2 > air > O_2$. Iron release from siderite was slowed by formation of iron oxide coatings on siderite surfaces in H_2SO_4. Siderite in KHP formed no coatings. Siderite reacts slowly with dilute acid at room temperature but will react rapidly at modestly elevated temperatures. This can result in errors in acid/base accounting methods used for overburden and topsoil substitute evaluation when siderite is present.

Additional Key Words: acid/base accounting, reclamation, iron oxides

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Introduction

Mining for lignite will disturb large areas of land in Texas. It has been estimated that one million acres could be disturbed by surface mining in the state and would require reclamation to restore the land to an acceptable level of productivity (Hossner and O'Shay, 1985).

Reclamation of surface mined lands requires the identification and treatment of potentially toxic or acid forming material (AFM) (Department of Interior, 1978; Railroad Commission of Texas, 1983). Acid/base accounting (Grube et al., 1971; Sobek et al., 1978) of overburden is being used in Texas as a criterium to evaluate the suitability of material for surface placement prior to reclamation. If sampling and chemical analyses are accurate and the acid/base account is positive, the material may be suitable as a topsoil substitute. If the acid/base account is negative, the overburden may not be suitable as topsoil or may require amendments be added prior to its use.

Preliminary work (O'Shay, 1982) indicated a relative abundance of siderite ($FeCO_3$) in Texas overburdens and difficulties in accurately determining acid/base accounting when this mineral was present in the sample. This could result in potentially acidic overburdens having acceptable acid/base accounting values when analyzed in the laboratory.

Acid/base accounting, as used by the Texas Railroad Commission, is the difference between the acidic plus acid forming and basic constituents in the sample. It is determined by subtracting the potential acidity (PA) and exchangeable acidity (EA) from the neutralization potential (NP).

$$\text{A/B Accounting} = NP - (PA + EA) \qquad (1)$$

The NP can be determined by treatment of the sample with acid followed by titration of the excess acid with standard base (Sobek et al., 1978). An alternative procedure for determining NP has been proposed by the Texas Railroad Commission. Neutralization potential is calculated after determining the inorganic carbonate content and the cation exchange capacity (CEC).

$$NP = CaCO_3 + 0.2\ CEC \qquad (2)$$

Inorganic carbon can be determined by the method described in Allison and Moodie (1965) or Bundy and Bremner (1972). The overburden is treated with an excess of acid and $CaCO_3$ calculated from the amount of carbon dioxide evolved.

Potential acidity is normally determined by one of three methods. 1) The total sulfur content of the overburden can be measured by dry combustion in an induction furnace followed by iodometric titration (Sobek et al., 1978). All sulfur is assumed to be due to pyrite so the PA can be calculated based on the stoichiometry of pyrite oxidation; 2) the ASTM (1968) method which is based on non-pyritic Fe and S being extracted with HCl followed by selective dissolution of pyrite with HNO_3. The PA is calculated from the amount of Fe or S associated with the pyrite; and 3) pyrite is determined directly by H_2O_2 oxidation followed by titration of H^+ produced by oxidation of the pyrite to iron oxide and H_2SO_4 (Grube, 1971; O'Shay, 1982). Any carbonates are assumed to be removed by an acid soak.

Siderite, if present in the sample, can interfere with determination of the acid/base accounting in several ways. Siderite reacts slowly with acids at room temperature to release CO_2. If the acid neutralization method is being used, an error is introduced due to neutralization of the acid by siderite:

$$FeCO_3 + 2HCl = FeCl_2 + H_2O + CO_2 \qquad (3)$$

Carbon dioxide is also given off in this reaction so direct determination of CO_2 to calculate $CaCO_3$ content can be in error.

Pure siderite weathers to form goethite, FeOOH (Dixon et al.,1982). Also formed are amorphous iron oxyhydroxides (Postma, 1983) and hematite, Fe_2O_3 (Seguin, 1966). Siderite oxidizes according to the following equations (Lindsay, 1979).

$$FeCO_3 + 2H^+ = Fe^{2+} + CO_2 + H_2O \qquad (4)$$

$$Fe^{2+} = Fe^{3+} + e^- \qquad (5)$$

$$3H_2O + Fe^{3+} = Fe(OH)_3 + 3H^+ \qquad (6)$$

$$FeCO_3 + 2H_2O = Fe(OH)_3 + CO_2 + H^+ + e^- \qquad (7)$$

The net reaction of siderite oxidation is acidic rather than basic due to oxidation and subsequent hydrolysis of Fe. Therefore, the presence of siderite in samples used for determination of NP for acid/base accounting can result in a substantial error due to the initial reaction (Equation 4). However, in nature where the reaction is allowed to go to completion, the net reaction is expected to be acidic (Equation 6).

Oxidation of Siderite

Seguin (1966) documented the time required for siderite dissociation. A grain size of less than 300 mesh would take approximately 35 years and a grain size between 60 - 100 mesh would take approximately 370 years to dissociate in air at room temperature. Under conditions of temperature and acidity used to determine NP, siderite would be expected to react rapidly and elevate the level of inorganic carbonates detected in the overburden. This would result in a higher NP than actually exists and could lead to the conclusion that the overburden material may have a suitable acid/base account when in reality the account could be negative.

Objective

The objective of this study was to determine siderite weathering as measured by solution Fe when incubated in acid solution under varying gaseous environments.

Materials and Methods

The siderite used in this study was collected from unoxidized surface mine overburden. The fresh siderite was placed in a plastic bag and stored in a freezer until used in this study.

The siderite sample was characterized by X-ray diffraction (XRD) (Figure 1) and chemical analyses. The XRD patterns were evaluated using the Mineral Powder Diffraction File (1980). Based on the XRD pattern, the sample used in this study contained siderite and a small amount of quartz. All of the siderite pieces used in the Fe release study were cut from a single siderite rock. The siderite rock was cut into blocks approximately 1 x 2 x 0.5 cm in size. The blocks were ground to a uniform surface area then freeze dried and weighed.

The rate of iron release was determined by placing freshly prepared blocks into solutions of potassium hydrogen phthalate (KHP), pH 3.0, or H_2SO_4, pH 3.0. Carbon dioxide, O_2, or air was bubbled through the solution to maintain a constant gaseous atmosphere. The solutions were changed regularly to maintain a pH below 4.5. Initially, 100 mls of solution were added to each container. To insure pH values below 4.5 at all times, it was necessary to increase the amount of solution to 200 ml. The H_2SO_4 solutions were changed daily and the KHP solutions were changed every 48 hours and an aliquot was saved for Fe analysis on a Perkin-Elmer Atomic Absorption Spectrometer (model 603). Solution pH was checked every 12 hours for the first 15 days and every 24 hours on all samples after 15 days.

The rate that siderite and $CaCO_3$ neutralized H_2SO_4 was determined by pH-stat titration. A sample of the fresh siderite was crushed and sieved. The sample was freeze dried and stored in a helium purged desiccator until analysis. A 20 mg sample of siderite or $CaCO_3$, crushed finer than 74 um, was titrated with 0.5 *N* H_2SO_4. A Copenhagen Radiometer automatic titrator equipped with an extended time pH-stat unit was used. Nitrogen purge gas was injected above the solution to prevent a build up of CO_2. The gas was first hydrated to reduce evaporation of the sample solution.

Results

Iron release from siderite blocks was carried out at ambient laboratory temperature. The temperature in the laboratory was 24 ± 2° C except during the 7 to 13 day period when the temperature increased to about 29° C due to an air conditioning failure. Daily iron release from siderite in the KHP solutions nearly doubled during this period (Figure 2). Iron release from the H_2SO_4 solution increased only slightly.

The siderite blocks incubated in H_2SO_4 solution formed an insoluble Fe^{3+} oxide on the block surface. As the Fe^{2+} released from the siderite weathering

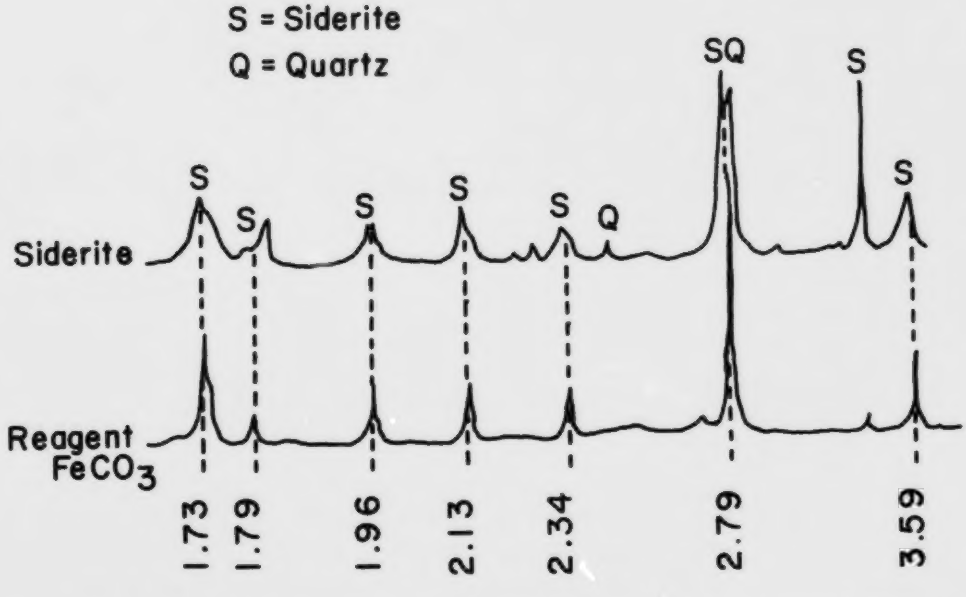

Figure 1. XRD patterns of siderite compared to reagent $FeCO_3$. The d-spacings are given in angstroms.

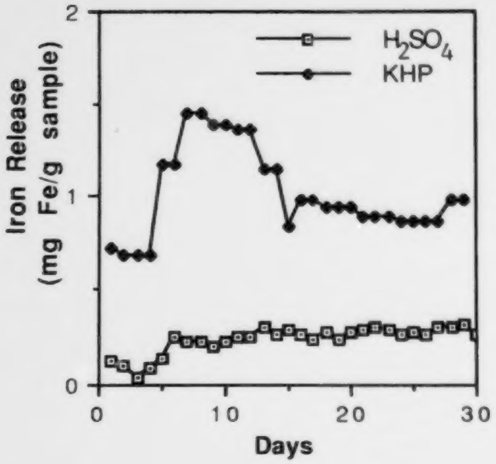

Figure 2. Iron release from siderite over a 30 day period in sulfuric acid or in potassium hydrogen phthalate (KHP) when incubated in air.

comes in contact with an electron accepter, it is oxidized (equation 5). The Fe^{3+} then forms an oxide (equation 6) and precipitates (Schwertman and Taylor, 1977). Siderite blocks incubated under air in H_2SO_4 had a bright red Fe oxide surface coating on the fourth day of the experiment. Based on the color this was assumed to be a coating of hematite. By day 12, siderite blocks under air and O_2 atmospheres in H_2SO_4 were a dark red color. The blocks under CO_2 had a brown coating. Data presented in Table 1 show the samples, treatments, and the color of the surface of the block surface. Munsell colors of the block surface were determined on day 30 of the study. All colors were determined on wet samples.

Table 1. Munsell colors for the the surface of siderite blocks incubated in H_2SO_4 or potassium hydrogen phthalate (KHP) under O_2, CO_2 or air at 30 days.

GAS	SOLUTION	COLOR	MUNSELL
O2	H2SO4	dark reddish brown	5YR3/4
O2	H2SO4	dark reddish brown	5YR3/4
O2	KHP	gray	5Y5/1
O2	KHP	dark gray	5Y4/1
Air	H2SO4	yellowish red	5YR4/6
Air	H2SO4	dark reddish brown	5YR3/4
Air	KHP	dark gray	5Y4/1
Air	KHP	gray	5Y5/1
CO2	H2SO4	dark brown	7.5YR4/4
CO2	H2SO4	strong brown	7.5YR5/6
CO2	KHP	gray	5Y5/1
CO2	KHP	dark gray	5Y4/1

Sample surfaces incubated in KHP were gray to dark gray regardless of incubation atmosphere; this is the color of unoxidized siderite (Mason and Berry, 1968). The KHP is buffered and maintained a pH near 3. In addition, the phthalate ion ($HC_8H_4O_4^-$) is capable of complexing Fe to some degree. Therefore, the Fe remains in solution instead of precipitating as Fe oxides on the siderite surface.

Siderite samples in H_2SO_4 and incubated under a CO_2 atmosphere, had coatings with Munsell colors that corresponded to colors for lepidocrocite, goethite and ferrihydrite (Schwertmann and Taylor, 1977). When Fe^{3+} salts are hydrolyzed rapidly at room temperature, ferrihydrite formation is favored.

The solubility of ferrihydrite increases with decreasing pH and goethite forms from the dissolution of ferrihydrite in increasing amounts with decreasing pH. Lepidocrocite and goethite are polymorphs with goethite having the highest stability. High concentrations of CO_2 favor the formation of goethite over lepidocrocite (Schwertman and Taylor, 1977). Senkayi et al. (1989) found that goethite formed from siderite in a 0.1 *N* H_2SO_4 solution when gaseous mixtures of CO_2 and O_2 were bubbled through a boiling suspension. It is most likely that the blocks incubated under an atmosphere of CO_2 are coated with goethite.

The coatings on the siderite blocks, incubated under air and O_2 environments had Munsell colors that correspond to lepidocrocite and ferrihydrite (Schwertmann and Taylor, 1977). It was concluded that the precipitate coating the blocks was ferrihydrite.

Over time, solution pH values increased less between solution changes so the siderite was remaining in a more acid environment over a longer period of time (Figure 3). The amount of Fe release increased slightly at the lower pH values. This indicates that Fe release from the siderite was being decreased by the iron oxide coating.

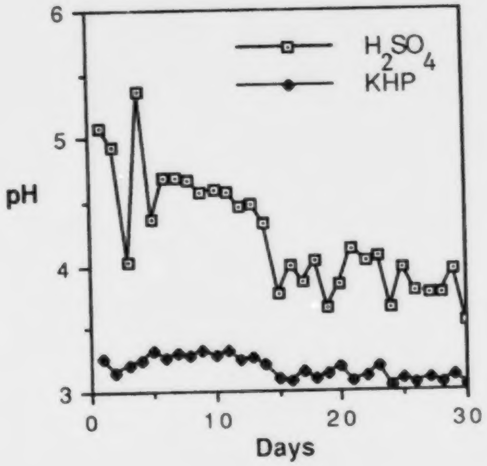

Figure 3. Daily pH of H_2SO_4 and potassium hydrogen phthalate (KHP) solutions containing siderite incubated in air.

Cumulative Fe release from siderite as influenced by incubation solution and gaseous environment is shown in Figure 4 for KHP and in Figure 5 for H_2SO_4. The siderite samples in KHP had greater loss of Fe compared to H_2SO_4. Of the three gas treatments, siderite in KHP under a CO_2 atmosphere had the highest release of Fe. Siderite under O_2 in H_2SO_4 had the lowest Fe release.

The Fe oxide coating formed on the surface of siderite in the H_2SO_4 solutions appears to slow the rate of Fe release compared to the uncoated KHP samples. Solution pH values in air and O_2 treatments were similar. Siderite in air developed an Fe oxide coating before siderite in O_2 followed by siderite in CO_2.

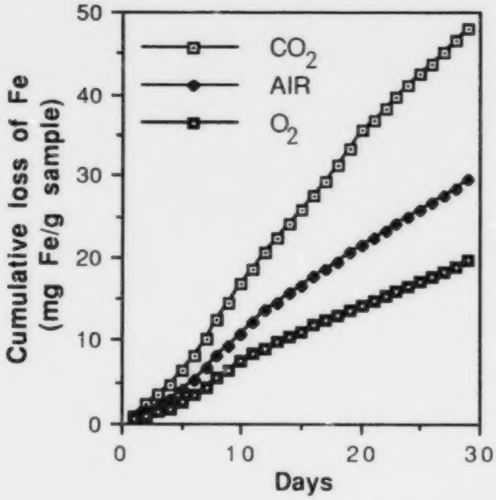

Figure 4. Cumulative iron loss from siderite incubated for 30 days in potassium hydrogen phthalate (KHP) solution under CO_2, air or O_2.

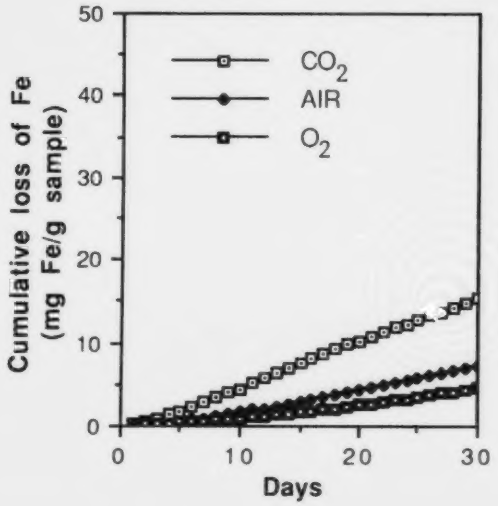

Figure 5. Cumulative iron loss from siderite incubated for 30 days in H_2SO_4 solution under CO_2, air or O_2.

The higher rate of Fe release from siderite under CO_2 is apparently due to the production of carbonic acid (HCO_3) and greater buffering capacity of the solution.

$$CO_2 + H_2O = H_2CO_3 \tag{8}$$

$$FeCO_3 + H_2CO_3 = Fe^{2+} + 2HCO_3^- \tag{9}$$

Reaction of < 74 um $CaCO_3$ and siderite at pH 3.0 is presented in Figure 6. All of the $CaCO_3$ was neutralized in about 30 minutes It took over 28 hours for the pH-stat titration of 20 mg siderite to approach 50 % completion.

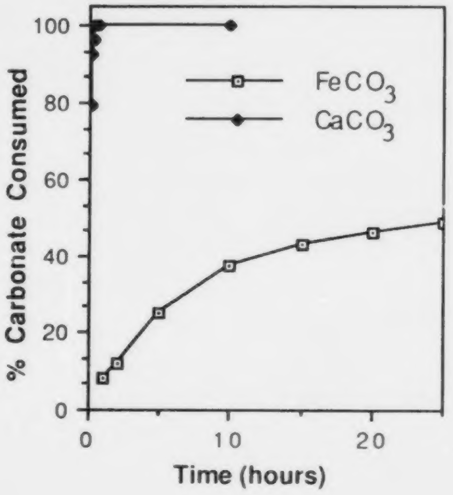

Figure 6. Percent carbonate consumed during the pH-stat titration of < 74 um siderite and calcium carbonate at pH 3.0.

Conclusions

1. Iron release from siderite in acid solutions was influenced by gaseous atmosphere and

decreased in the following order: CO_2 > air > O_2.

2. Iron oxide coatings formed on the surface of siderite when incubated in H_2SO_4 solutions initially at pH 3.0 under atmospheres of air, O_2 and CO_2.

3. Iron oxide coatings did not form on siderite incubated in solutions of KHP buffered at pH 3.0.

4. Iron release from siderite in H_2SO_4 solution was slowed by formation of Fe oxide coatings.

5. Reaction of siderite with dilute acid is slow at room temperature but rapid at elevated temperatures resulting in errors in acid/base accounting methods used for topsoil substitute evaluation.

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Physical And Chemical Characteristics Of Coal Prep Plant Wastes From Southwest Virginia[1]

Barry R. Stewart and W. Lee Daniels[2]

Abstract. Coal prep plant wastes are difficult to reclaim due to high potential acidity and coarse fragment content, low water holding capacity, low fertility, and other problems. Little is known about their properties, particularly as they relate to revegetation potential. This study was undertaken to determine the physical and chemical properties of composite samples from 27 coal waste piles of varying age. Selected physical and chemical properties varied widely across this sample set. The pH values varied from 8.3 to 3.0, and the older piles had lower pH values than the more recent piles. Base saturations ranged from 100% to 1% and, as expected, were highly correlated with pH values. The saturated paste electrical conductivity (EC) was higher in the younger coal waste materials. The mean coarse fragment (>2mm) content of these materials was 60%. The average texture of the fine (<2mm) fraction was a sandy loam with 15% clay. The mean water retention difference, between 10.0 J kg^{-1} and 1500 J kg^{-1} of soil moisture tension, in the fine fraction was 0.136 g water/g soil. These moisture retention values are very low when compared with those of natural soils, particularly in light of the wastes' high coarse fragment content. Double acid extractable P was generally low, but a few samples had high levels of P. Our results indicate that some low-S refuse materials would be suitable for direct seeding, but serious water holding and long term nutrient availability problems are likely.

Additional Key Words: Coal refuse, reclamation, Appalachian coal fields.

Introduction

Thousands of ha of coal prep plant wastes (aka coal refuse, gob, slate,) occur in the eastern United States and with each ton of coal processed this figure increases. In Virginia alone, there are over 4,000 ha of permitted coal refuse disposal areas. The exact area of abandoned coal refuse piles is not well documented but is considerable. Virginia alone has spent over $7 million on the stabilization and reclamation of abandoned coal refuse piles. This is above and beyond what private coal companies have spent to reclaim active refuse disposal areas, as required by the Surface Mining Control and Reclamation Act of 1977 (SMCRA). One hundred and thirty-five million tons of coal refuse were produced in the United States in 1983. Of this total 79% was coarse (> 0.5 mm) refuse (Khan et al, 1986) which was the subject of this study.

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Improperly reclaimed coal refuse piles pose an ominous threat to the quality of the surrounding environment through slope failures, surface erosion, and the production of acidic leachates. These materials are difficult to reclaim due to physical problems, high levels of potential acidity, high soluble salt levels, low concentrations of plant nutrients, low water holding capacity, and high summer heat levels. Current regulatory policies require the use of a thick topsoil (1m) cover to reclaim active refuse disposal areas. This is an expensive and frequently impractical alternative in the Appalachian coal fields. Direct seeding of refuse is allowed only when long-term monitored trials indicate a high probability of reclamation success. Little comprehensive research has been conducted which would allow reclamationists to base restoration strategies on actual waste properties and conditions. There have been few studies in which the refuse properties were carefully evaluated, and then used to design replicated trials to evaluate the performance of different treatments.

The goal of this study has been to characterize the physical and chemical properties of coal refuse and then to relate important properties to reclamation potential. There have been a few studies which characterized coal refuse properties (Bland et al, 1977; Buttermore et al, 1978), but they did so from a total elemental, reprocessing standpoint. These studies do provide useful data on the range of refuse properties; however, they make no mention of reclamation potential.

Coal refuse will obviously share many characteristics with the associated coal seams. Mining, coal cleaning, and weathering processes also influence the properties of refuse. Criteria for the classification of mine soils were developed by Sencindiver (1977) and used to classify refuse soils by Delp (1975). In a study of 26 mine soils developed in coal refuse, Delp observed that the majority of surface horizons were topped with coarse fragments, local pockets of differing materials were common, and that rooting depth was dependent on soil pH. Buttermore and others (1978) analyzed coal refuse from seven mining districts in the eastern and midwestern United States, and observed that there was more variability within mining districts than between different mining districts. They also concluded that mining and cleaning methods (rather than geology) had the greatest influence on the elemental composition of coal refuse. We were unable to find a study in which the chemical properties of coal waste were evaluated using soil testing procedures, and then related to reclamation potential.

Materials and Methods

Sampled refuse piles were selected on the basis of coal seam, age of the pile, accessibility, coal company cooperation, and other factors. At least eight of the major coal producing seams of southwest Virginia were included in this sample set. Twenty-seven coal waste piles were sampled during the summers of 1986 and 1987. Large bulk samples (usually about 4kg) were obtained by combining several subsamples from each sampling site. The subsamples were taken at random across the walkable surface of each pile. On the larger piles one or two different representative areas were sampled. Erosional gullies, burned areas, toeslope positions, disturbed areas, and other nonrepresentative features were avoided during sampling. When possible, stable, noneroded positions were chosen for sampling. All samples were taken from the upper 10 cm of refuse. All coarse fragments larger than 15 cm were excluded at the time of collection. In addition to the refuse sample, information on the slope, aspect, age, and seam composition was recorded at each site. After collection, the bulk samples of refuse were taken to the laboratory for preparation and analysis.

All samples were air dried, sieved, and the percentage retained on a 2mm sieve recorded. A subsample of the coarse fragments (> 2mm) was retained for future analysis. The entire < 2mm fraction was retained for detailed analyses. Moisture desorption determinations at 10, 33, 100, 300, and 1500 J/kg soil moisture tension were performed on the < 2mm fraction of each sample using porous ceramic plates and pressure vessels. Refuse samples were placed in metal rings on the ceramic plates and were allowed to saturate by the procedure described by Richards (1965). Since most coal refuse shows limited development of soil structure, sample disturbance errors should be minimal. The soil moisture retention at each tension was then adjusted to reflect the entire refuse sample including coarse fragments. Particle size analysis by the hydrometer method of Day (1965) was performed on all samples. Weight loss at 923K, an estimator of carbon content, was determined by heating 5g of coal refuse for 3hr in a muffle furnace.

Soil pH was determined in a 1:1 soil:water slurry with a combination glass-calomel electrode and a pH meter (McLean, 1982). Electrical conductivities were determined from a saturated paste extract using a conductivity cell referenced to standard 0.01 N KCl (Rhoades, 1982). Extractable Ca, Mg, and K were determined by atomic absorbance spectrophotometry (AAS) after extraction with N NH_4OAc buffered at pH 7 (Thomas, 1982). Extractable Al was extracted with N KCl (Barnhisel and Bertsch, 1982). Cation exchange capacity was estimated by the summation of the extractable cations (Ca+Mg+K+Al)(Chapman, 1965). Percent base saturation was determined by dividing the sum of the basic cations by the total CEC.

Available P was extracted using a double acid solution, (0.05N HCl and 0.025N H_2SO_4), with subsequent colorimetric analysis as described by Olsen and Dean, 1965. Sodium dithionite-citrate-bicarbonate (DCB) was used to extract free-Fe (Holmgren, 1967) which was then determined using AAS. Total-Fe was determined using ion coupled plasma emission spectroscopy (ICPES) from a total digest using HF in a pressure bomb (Bernas, 1968) Total-S was determined using a LECO furnace S-analyzer.

Results and Discussion

For the purpose of limiting table size, six representative refuse materials were selected to illustrate the range of properties that are displayed by the 27 pile sample set for the tested parameters. The sample set mean is also presented for each parameter tested. These 6 samples represent 3 different ages of coal refuse. Locations MRP and KRP represent refuse that is approximately 60 years old, while locations PTH and RRP represent 30 year old material, and locations BMR and RRA represent active refuse disposal areas. The exact ages and the seam composition of each pile are given in Table 1.

The results of the sieve analysis and the particle size analysis on the <2mm fraction are presented in Table 2. The sample set mean of 59% >2mm is similar to the coarse fragment content reported by Buttermore et al. (1978) and Delp (1975) for refuse piles in this region. The majority of these materials had a sandy loam texture (<2mm), with a few being loamy sands and loams.

The coarse textured nature of these materials results in their having very low water holding capacities. This problem is compounded by the hydrophobicity of the carbonaceous surfaces in these materials. The relationship between soil moisture tension and water content for the six selected materials is shown in Figure 1. Site BMR has an exceedingly low water holding capacity. It is generated by a cleaning process in which the fines are removed and not recombined with the coarser material after processing. Recombination of some fines with the coarse at such sites would result in a particle size distribution with a higher water holding capacity.

Obviously, these materials will pose severe drought stress problems if left unamended. This drought stress would be most pronounced on south facing slopes, and on narrow flat tops of refuse piles. This large potential for drought stress underscores the need for amendments which raise the water holding capacity of these materials. Mulch and topsoil covers would bring immediate improvement in water holding capacity. Cover crops would shade the surface and provide mulch, which would facilitate the establishment of other species of plants, especially legumes. Physical weathering with time will also reduce the particle size of these materials which will in turn improve water holding. Any measure taken to improve the amount of available water in these materials will markedly improve the probability of reclamation success.

The percent weight loss of these materials at 923k is also presented in table 2.

Table 1. Pile ages, and major seams for six selected refuse sites.

Location	age	seams in pile
MRP	1930's	Pochahantas
KRP	1927	Wilson
PTH	1954	Imboden
RRP	1953	Imboden
BMR	active	Dorchester,Imboden,Parsons
RRA	active	75% Dorchester + Norton 25% Clintwood

Table 2. Percent coarse fragments (>2mm), percent fine fraction, particle size analysis, and weight loss at 923K of six selected sites and the 27 pile sample set mean.

Sample	% >2mm	% <2mm	% Sand	% Silt	% Clay	% Wt. loss
MRP	40	60	77.0	0.2	22.8	43.4
KRP	65	35	44.3	20.4	35.3	28.0
PTH	66	34	75.9	15.7	8.4	62.6
RRP	45	55	65.4	25.2	9.4	53.8
BMR	66	66	78.0	13.5	8.5	36.9
RRA	56	44	53.6	26.7	19.7	30.8
Mean$^{(n=27)}$	59	41	61.8	22.5	15.6	32.4

This parameter is being used as an estimate of the amount of carbon or coal present in these samples. There may be errors due to de-hydroxylation of the 1:1 clay minerals and weight losses due to carbonates, but this parameter does provide a rough estimate of the carbon content. A trend of increasing coal cleaning efficiency with time can be seen in these data.

Soil pH is probably the most commonly tested soil chemical parameter. The pH of a material directly influences the availability of many plant macro- and micro-nutrients. The mean pH value for the sample set was 4.7 (Table 3). This value was skewed upward by a few high pH values; the median pH value was 4.2. The pH of fresh refuse samples varied widely, while older weathered samples were generally strongly to very strongly acidic.

The fresh refuse at site RRA had a near neutral pH, while the material from BMR had a pH of 4.2. This suggests that the pyrite in the latter sample had started to oxidize. Total-S values are also presented in Table 3. In general, these values are low and are within the range reported by others who have examined refuse in the East (Buttermore 1975, Williams 1976). There is an obvious relationship between total-S content, extractable Al content, and pH within the three age groups represented (Table 3), and in the sample set as a whole.

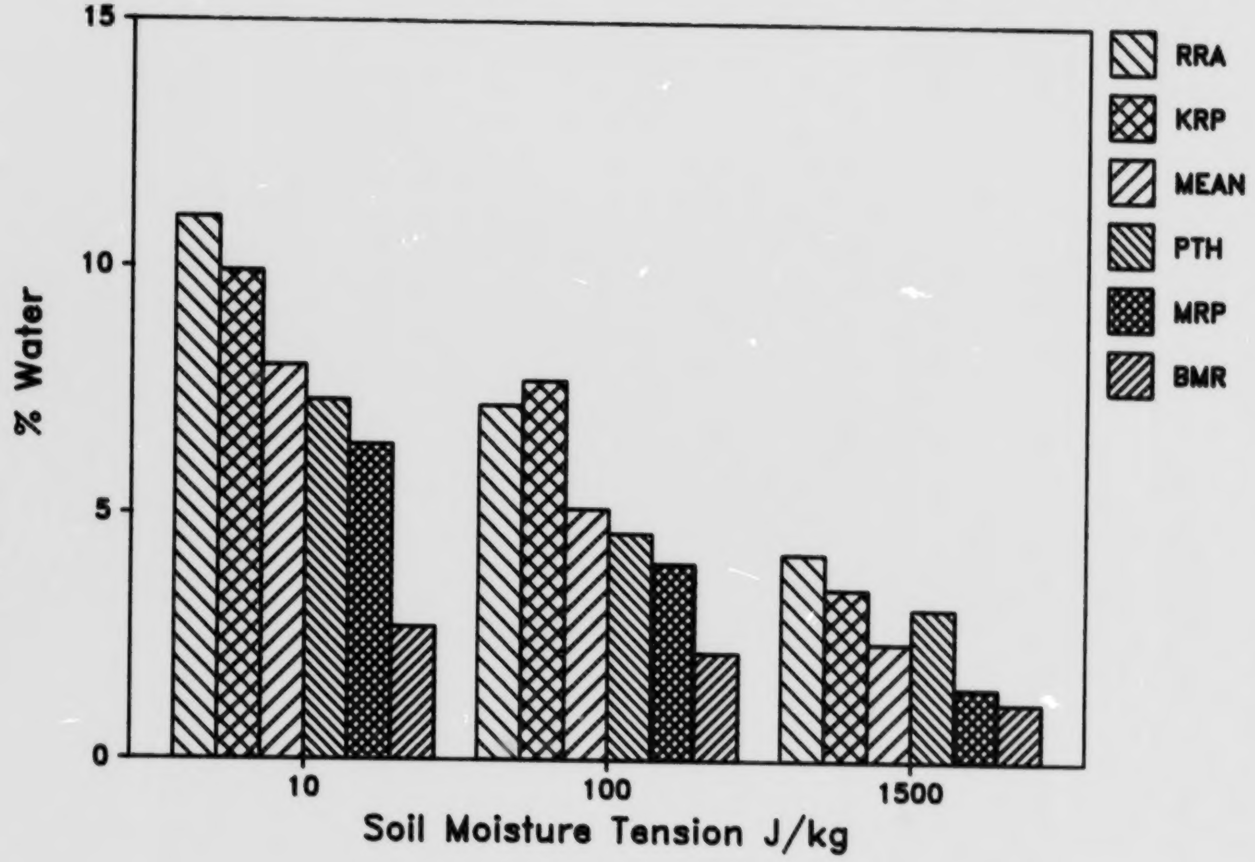

Fig. 1 *Percent water held at 3 soil moisture tensions.*

Table 3. The pH, cation exchange capacity (CEC), N KCl extractable Al, % base saturation, Total-S, and double acid extractable P for six selected sites and the 27 pile sample set mean.

Sample	pH	Conduct.	CEC	ext Al	% BS	% Tot-S
		dS/cm*	----cmol/kg----			
MRP	5.6	0.148	5.1	0.34	93.3	0.27
KRP	3.6	0.328	8.1	7.03	13.2	1.04
PTH	4.0	0.200	6.7	6.40	4.5	0.53
RRP	6.4	0.438	7.4	0.10	98.6	0.28
BMR	4.2	5.510	17.4^{+}	1.36	92.0	1.43
RRA	7.1	3.580	7.9	0.20	97.5	0.54
Mean$^{(n=27)}$	4.7	0.923 #@	8.0	3.33	51.9	0.42

* deciSieman/cm.
+ value affected by soluble salts
@ mean for 3 active piles 4.203 dS/cm.
# mean for rest of sample set excluding active piles 0.496 dS/cm.

Table 4. Percent dithionite-citrate bicarbonate extractable Fe, percent total-Fe, and double acid extractable P of six selected sites and the 27 pile sample set mean.

Sample	% DCB ext Fe	% Tot. Fe	DA ext. P
			ppm
MRP	0.85	3.00	24.8
KRP	4.49	6.66	5.1
PTH	0.53	4.27	1.1
RRP	0.38	3.38	2.7
BMR	0.54	5.00	24.0
RRA	2.76	4.76	26.8
Mean$^{(n=27)}$	1.45	3.95	17.8

The piles with the higher sulfur contents have lower pH values and larger amounts of extractable Al. This is due to the acidity generated by pyrite oxidation, which attacks the alumino-silicate mineral structures and releases Al. The CEC values of these materials are generally low, and those piles with pH values <5 are heavily saturated with Al (Table 3). The exception to this trend is the BMR refuse which contains a large amount of soluble salts. The reported CEC and base saturation for BMR are probably high, due to soluble salt errors. The low CEC values in these materials results in a low nutrient holding capacity and the possibility of surface and ground water pollution through runoff.

Salt solutions used in coal cleaning, and the salts generated by acid sulfate weathering processes frequently lead to elevated levels of soluble salts in refuse materials. Electrical conductivity provides an indirect way to measure the amount of soluble salts in a material. Conductivities of > 2 dS/cm have been shown to be detrimental for the growth of some plants (Bower and Wilcox, 1965). The sample set mean conductivity is skewed upward, due to the high conductivities of the three active refuse piles in the sample set (Table 3). The mean for the three active piles is 4.2 dS/cm, while the mean for the 24 older piles is 0.49 dS/cm. The conductivity of the three active piles is above the 2 dS/cm value, which has been reported to be toxic to some plants. No other piles had a conductivity greater than 2.0 dS/cm. As fresh refuse weathers, many salts are generated, and with time these salts are leached. It may be beneficial to allow the conductivity to decrease through weathering and leaching before a reclamation effort is attempted.

An easily determined parameter that could be used to quantify the amount of weathering with time in refuse would be beneficial. "Free" (DCB extractable) Fe/total-Fe values were evaluated to see if this parameter correlated well with time. DCB-Fe and total-Fe data are presented in Table 4. The 27 pile sample set mean DCB-Fe:total-Fe ratio is 35%, however there is a large variation within the sample set. No clear relationship between DCB extractable Fe and total-Fe with time was observed. This could be due to the weatherability of different sizes of iron pyrite grains. Very fine grained pyrite will weather much faster than large grained pyrite (Caruccio, 1970).

There is a large amount of variability in the amount and availability of plant nutrients in coal refuse. This variability is illustrated by the nutrient P. The sample set mean of 17.9 ppm (Table 4) is skewed by a few very high values. The sample set median value is 7.6 ppm. Fourteen of the 27 samples extracted had double-acid-extractable-P values that fell into the low category on the plant availability index of Olsen and Dean (1965). One probable sink for P in refuse are Fe and Al phosphate compounds that form, especially in the more acidic materials. The wide variability in available P illustrates the need for testing of each pile instead of relying on a blanket recommendation for a region.

Conclusions

It appears that some refuse materials should be suitable for direct seeding if the proper surface amendments are applied. Adverse physical properties (low water holding capacity) must be addressed with amendments such as mulch or topsoil, if long-term reclamation success is to be achieved. In fresh refuse piles, sulfate salts may be a problem until oxidation slows and the salts are leached. Low pH and infertility can be rectified through liming and fertilization, but long-term nutrient retention and fixation problems are likely.

Variability of coal refuse properties, microclimate, and other soil/site conditions make the development of uniform reclamation strategies difficult. Reclamation planning is also further complicated by the fact that the physical and chemical properties of refuse will change considerably with time. An integrated refuse classification/ reclamation system is needed, along with dedicated trials to document the response of various types of refuse to various reclamation treatments.

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THE FACTORS INFLUENCING CONE PENETROMETER RESISTANCE AS A MEASURE OF COMPACTION IN MINESPOILS[1]

by

D.J. Thacker and R.L. Johnson[2]

Abstract. Cone penetration resistence as a measure of compaction was used to evaluate minespoils from the Luscar geological formation of the Alberta Rocky Mountain Foothills across the plant available moisture range. Three soil textures, two salinity levels and six moisture tensions were tested. There was a well defined relationship between cone penetration resistence, or strength, and moisture tension. Average minespoil strength at 1/3 and 3 bars moisture tension was 40% and 72% of that at 15 bars tension, respectively. Because each minespoil has a different range of cone penetration resistence, depending mainly on texture, an absolute relationship between moisture tension and strength could not be developed. By normalizing the strength values, whereby all values were divided by that obtained at 15 bar moisture tension, a predictive equation relating strength to moisture tension is reported ($r^2 = 0.92$) that is applicable to a wide range of minespoil textures. Clay content and salinity had a significant effect on minespoil strength. Penetration resistance was 2.5 times greater at 33% clay content than at 8% clay. Minespoil strength of saline spoils was 1.25 times that of non-saline spoils. The salinity effect increased as salts precipitated upon drying the minespoil: strength at 15 bars moisture tension in saline minespoils was 1.4 times that of non-saline minespoils.

Additional Key Words: compaction, strength, effect of moisture tension, effect of salts.

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Introduction

The effective reclamation of coal minespoils involves the rapid establishment of a healthy vegetation cover. Problems such as poor seedbed conditions and lack of nutrients are overcome by covering spoils with a layer of topsoil and by fertilization. This allows germination and seedling establishment, but further development of the cover is largely dependent on subsoil (spoil) conditions. The lack of organic matter in spoils does not promote good soil structure, and a poorly structured spoil with relatively high bulk density can result. The spoil can have high strength values which are directly related to reduced root growth (Barley 1963, Taylor and Gardner 1963, Thacker and Johnson 1988).

Measurements to identify subsoil compaction are not routinely taken because of problems of collecting and interpreting strength data. Strength can be measured inexpensively and rapidly by a newly developed cone penetrometer (James 1988), but readings are highly dependent on soil moisture (Greacen 1960, Singh and Ghildyal 1977). If the relationship between moisture and penetration resistance was defined, it would allow strength readings made at one moisture tension to be used to estimate strengths at other moisture tensions. The need for remedial action could be assessed by comparing measured and estimated strengths in the plant-available moisture range to known values at which root growth is limited.

Research has shown that penetration resistance values are dependent on moisture tension, soil type and bulk density (Taylor and Gardner 1963, Ayers and Perumpral 1982), which makes necessary a calibration curve for each soil or spoil. However, changes in strength, normalized to account for the differences due to water holding capacity, may be independent of soil type and density. If this were the case there would be no need for calibration curves for each soil or spoil. A single graph or equation showing the relative change of strength due to the change in moisture tension could be used for a wide range of soils and spoils.

The purpose of this paper is to define the relationship between strength and moisture tension in minespoils of different clay and salt contents to determine whether a single moisture-strength relationship is valid over a range of minespoil conditions.

Materials and Methods

Seventeen minespoils from the Luscar geological formation of the Rocky Mountain Foothills were air-dried and crushed to pass a 2 mm sieve. The methods used to determine chemical and physical data for these samples along with a comprehensive listing of results is described by Thacker (1987). The chemical and physical data presented in this paper are summarized from those results.

Three minespoils chosen to represent fine, medium and coarse textures were selected. Particle size analyses were done in triplicate.

Five kilogram subsamples of each minespoil were used for salinization and desalinization. The goal was to end up with high and low electrical conductivities in saturation extracts. The average chemical composition of saturation extract solutions from the saline spoils of the Luscar formation (Thacker 1987) was duplicated in the salinizing solution. On a milliequivalent basis cations in the extracts were: 95% sodium, 2% calcium, 2% magnesium and 1% potassium. Chloride was the dominant anion. A 500 millequivalent per litre stock solution was made with this composition.

To determine the amount of solution needed to salinize the minespoils, various amounts of the solution were added to 150 g samples of minespoil, the sample was moistened with distilled water, mixed, left overnight and a saturation paste extract made and analyzed the next day. When the correct volume of solution was determined for each minespoil, the salinization treatment was performed on the remaining spoil, with mixing accomplished by rotating the sample for 3 hr in a rotating-drum mixer. The spoil was then oven-dried, ground to pass a 2 mm sieve and thoroughly remixed.

To desalinize spoils five kilograms of each spoil were placed in 25 cm diameter pots with several layers of Whatman #40 filter paper covering the drainage holes. The spoils were leached slowly with 10 L of calcium chloride solution (50 g $CaCl_2$/L) and then flushed slowly with approximately 20 L of distilled water until the water draining from the pots had an electrical conductivity less than 0.1 dS/m. The spoils were then oven-dried, ground and mixed as for the salinized spoil.

Minimum and maximum bulk density values were measured for each minespoil. The minimum bulk density was defined as the bulk density obtained after pouring air-dry, loose spoil into a container and tapping lightly to allow settling. The maximum bulk density was obtained by compressing moist spoil into a 15.2 cm diameter, 3 cm deep, PVC ring by means of a three tonne hydraulic jack until no additional spoil could be forced into the volume. Small holes in the PVC ring allowed drainage during compaction. The bulk density used in the experiment was the average of the minimum and maximum bulk densities for each spoil (to the nearest 0.05 g/cm^3); compression was done in the PVC rings described above.

A pressure-plate apparatus is not effective for moisture equilibration when soil is held in rigid-walled containers because the soils often shrink slightly upon drying causing loss of contact between the soil and pressure-plate. To overcome this problem 18 gypsum blocks were individually calibrated in a bed of medium textured, Chernozemic soil in a pressure-plate at 1/3, 1, 3, 5, 10 and 15 bars moisture tension. One of the gypsum blocks was buried in the centre of each ring of compacted spoil just below the spoil surface and was used to monitor the increase in moisture tension of the spoil as it air-dried. By air-drying the spoils the salt content remained constant throughout the experiment.

Strength was measured as penetration resistance at 1/3, 1, 3, 5, 10 and 15 bars moisture tension by manually pushing a 30°, 0.5 in^2 penetrometer cone into the spoil until the base of the cone was flush with the spoil surface. The ring of compacted spoil rested on an electronic balance which was used to monitor the applied force. The force was converted from kilograms to megaPascals (MPa) of pressure based on the basal area of the penetrometer cone.

The experiment was designed to allow an analysis of variance using three replicates of 36 treatments (3 spoils x 2 salinity levels x 6 moisture levels = 36 treatments). Strength was the response variable.

Results and Discussion

Chemical and physical data for the samples are presented in Table 1. The three minespoils have distinctly different clay, silt and sand contents providing a considerable range of texture to evaluate the moisture-strength relationship. The medium textured minespoil has a much lower minimum bulk density (1.07 g/cm^3) than either the coarse (1.42 g/cm^3) or fine (1.41 g/cm^3) minespoils. This also results in a much lower average bulk density for the medium minespoil. The electrical conductivity of the non-saline minespoil is <2 dS/m; the saline minespoil has an electrical conductivity of >7 dS/cm. Minespoil pH is not affected by the addition or removal of soluble salts, but the medium texture spoil has a much lower pH than the other two.

An analysis of variance was done to identify factors and interactions that influence minespoil strength (Table 2). Minespoil type, moisture tension and electrical conductivity (salt content) all have a significant effect on strength.

The significant effect of minespoil type on strength must be related to differences in particle size distribution and related changes in bulk density. The possibility that the effect is due to changes in clay mineralogy is unlikely. For minespoils originating from the Rocky Mountains, a change in mineralogy is often associated with a corresponding change in saturation percent (Thacker 1987). In this case the increase in saturation percent parallels the increase in clay content (Table 1); and therefore mineralogy can be ruled out as a major factor causing differences in minespoil strength. The fine textured minespoil has the highest mean strength (1.42 MPa), and the coarse minespoil has the lowest mean strength (0.57 MPa).

Table 1. Chemical and physical data for minespoils.

Property	Minespoil		
	coarse	medium	fine
Clay (%)	8	18	33
Silt (%)	13	21	43
Sand (%)	80	61	24
Texture	loamy sand	sandy loam	clay loam
Min. B.D.[a] (g/cm^3)	1.42	1.07	1.41
Max. B.D. (g/cm^3)	1.70	1.65	2.00
Average B.D. (g/cm^3)	1.55	1.35	1.70
Non-saline E.C. (dS/m)	0.7	1.6	1.1
Saline E.C. (dS/m)	11.1	7.1	8.2
Non-saline pH	7.9	4.9	8.0
Saline pH	8.0	5.0	8.4
Saturation (%)	31	38	42

Table 2. Analysis of variance for minespoil strength.

Source of variation	df	Sum squares	F
Total	107	2715	32.1*
Error	72	164	
Treatments			
Minespoil	2	1517	333.9*
Moisture	5	646	56.9*
Salinity	1	115	50.4*
Interactions			
Minespoil/Salinity	2	91	20.1*
Minespoil/Moisture	10	124	5.4*
Salinity/Moisture	5	40	3.5*

[a] Treatments designated with an asterisk (*) are significant at a 95% confidence level. Unmarked figures are not significant at 95%.

There is a non-linear relationship between clay content and minespoil strength (data not shown).

The greater penetration resistance associated with increased clay content can be attributed to an increase in the number of small soil pores. Strength is determined by frictional forces, cementing agents and the strength and number of moisture bonds between particles (Aitchison 1961, cited by Mirreh and Ketcheson 1972). As moisture tension increases large pores are drained, and smaller pores control water retention. The water in the small pores has much greater curvature radii which markedly increases interparticle cohesion (Gardner 1961, cited by Mirreh and Ketcheson 1972). The greater the number of small pores, the greater is the cohesion (strength) as the soil or spoil dries.

The two salinity levels result in significantly different penetration resistance; values of the saline spoils (>7 dS/m) are 1.25 times those of the non-saline minespoils (<2 dS/m). However, the effect on strength amounts to only one sixth that caused by changes in clay content or moisture (data not shown).

The significant interaction between minespoil and electrical conductivity indicates that salinity has a different effect on penetration resistance in different spoils. Strength values at high salinity (>7 dS/m) were 2.3 times those at low salinity (<2 dS/m) for the coarse textured spoil (0.80 vs. 0.35 MPa); 1.2 times for the medium textured spoil (0.75 vs. 0.63 MPa); and only 1.03 times for the fine textured spoil (1.44 vs. 1.40 MPa). In the coarse minespoil less water is present at all moisture tensions than in the spoils with finer textures, so the coarse spoil has the greatest content of precipitated salts and the most pronounced effect of salt cementation.

There is also a significant interaction of moisture and salinity on strengths indicating that the effect of salinity on strength is dependent on moisture. Apparently, the salt-cementation effect only becomes substantial when salts are precipitated in relatively dry soils. In moist soils salts are dissolved, and cementation is less obvious.

Moisture tension, as expected from a review of the soil compaction literature (Graecen 1960, Taylor and Gardner 1963 Ayers and Persumpral 1982), has a significant influence on penetration resistance (Table 2). Average minespoil strength at 15 bars moisture tension is 2.6 times that at 1/3 bar tension. This is similar to the increase associated with an increase in clay content from 8% to 33%, where strength increased 2.5 times.

The significant interaction between minespoil type and moisture (Table 2) indicates that the effect of moisture on penetration resistance is different in different minespoils. This is illustrated in Figure 1 where the moisture-strength curves differ between minepoils. Compared to strength at field capacity, values at wilting point are 2.4 times as great for the low-clay spoil, 3.3 times as great for the medium-clay spoil and 2.5 times as great for the high-clay spoil.

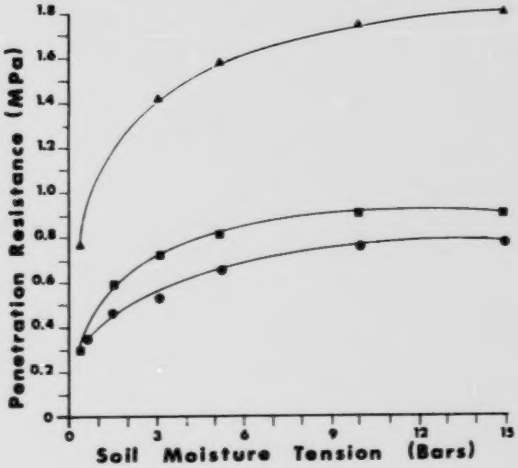

Figure 1: Penetration resistance vs. moisture tension in fine(▲), medium(■), and coarse textured (●) minespoils.

One of the objectives of this study was to develop a relationship between minespoil strength and moisture tension such that one measurement of both could be used to estimate the changes minespoil strength would undergo with wetting or drying. Figure 1 makes it obvious that there is a well defined dependence of strength on moisture tension. But the large differences in absolute strength at the same moisture tension between minespoil types shows that texture must be taken into account.

By normalizing the minespoil strength values (dividing the strength at each moisture tension by the strength at 15 bars moisture tension), a precise prediction of minespoil strength can be achieved (Figure 2). After normalization the influence of minespoil type is removed; strength is shown to depend only on moisture tension.

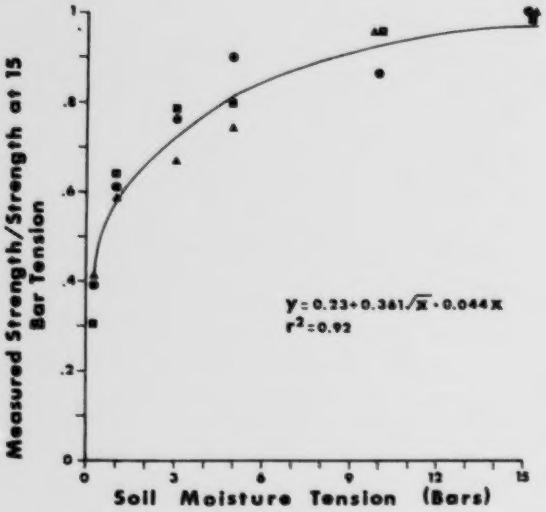

Figure 2: Normalized soil strength vs. moisture tension in fine(▲), medium(■), and coarse textured (●) minespoils.

Using this figure or the regression equation, one can predict an unmeasured minespoil strength at any moisture tension from one measured strength and one measured moisture tension:

$$Y_t = A_b \cdot \frac{Z_t}{X_b} \tag{1}$$

where: Y_t = predicted strength at desired moisture tension

A_b = actual strength at measured moisture tension

Z_t = Normalized strength at desired moisture tension (from Fig. 2)

X_b = Normalized strength at measured moisture tension (from Fig. 2)

For example, if the measured moisture tension is 3 bars and the measured minespoil strength 2.0 MPa, then minespoil strength at 1/3 bar and 15 bars moisture tension would be:

$$Y = 2.0 \cdot \frac{0.4}{0.72} = 1.1 \text{ MPa at 1/3 bar}$$

$$Y = 2.0 \cdot \frac{1.0}{0.72} = 2.8 \text{ MPa at 15 bars}$$

Since the minespoils used in this experiment all came from one area of Alberta, it is important to evaluate the validity of this predictive method on spoils with a wider range of properties.

Previous studies in soils (Taylor and Gardner 1963) and spoils (Thacker and Johnson 1987) have shown that 2.5 MPa (25 bars) strength can be considered a limit to unimpeded root growth. Above this value root growth decreases rapidly. Therefore, the strength estimates generated from equation 1 can be used to evaluate the probability of minespoil compaction affecting root performance across the entire range of moisture contents.

Conclusions

Texture, moisture and salinity all exert significant effects on minespoil strength as measured by penetration resistance. Strength values at 33% clay content were 2.5 times those at 8% clay; strength at 15 bars moisture tension was 2.6 times that at 1/3 bar tension; and strength at high salinity (>7 dS/m) was 1.25 times that at low salinity (<2 dS/m).

There is a precise (r^2 = 0.92) dependence of normalized strength on moisture tension regardless of minespoil type or salinity level. (Normalized means that all measured strength values were divided by the strength value at 15 bars moisture tension). Therefore, the strength of a minespoil at any moisture tension can be predicted from only one, strength-moisture tension measurement. This allows for changes in penetration resistence (strength) due to fluctuations in moisture content to be taken into account when evaluating the effect of compaction on plant performance.

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Acid Generating Materials

Session Chairmen: G.E. Schuman and W.L. Daniels

CHARACTERIZATION OF LEACHATE PRODUCED FROM SULPHUR-CONTAMINATED SOILS[1]

by

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Abstract. Reclaiming soils that are heavily contaminated with elemental sulphur is a problem specific to a small part of the oil and gas industry. Characterization of leachate produced from sulphur-contaminated soils will aid in the evaluation of potentially related environmental and health impacts. Leachate was collected at initiation and completion of a greenhouse growth trial from pots containing four sulphur levels (<0.1%, 4%, 9%, and 14% total sulphur) and four reclamation treatments(no treatment, limestone, limestone and manure, and manure). Leachate samples were analyzed for pH, electrical conductivity, nitrate-nitrogen, ammonium-nitrogen, sulphate-sulphur and phosphate-phosphorous. Selected subsamples were acidified and analyzed for soluble aluminum, iron and manganese. Leachate produced from unlimed, sulphur-contaminated soils were strongly acidic while the pH of leachate produced from limed, sulphur-contaminated soils was neutral. Electrical conductivity values were highest in leachate produced from unlimed, sulphur-contaminated soils. Leachate produced from unlimed sulphur-contaminated soils also contained elevated levels of nitrogen, phosphorous, and sulphur as well as elevated levels of soluble aluminum, iron and manganese. Leachate produced from limed, sulphur-contaminated soils contained elevated levels of sulphate-sulphur. Results obtained from this experiment indicate that a delay in neutralizing a soil that is heavily contaminated with elemental sulphur could cause a movement of soluble metals down the soil profile and may also cause a drain of potentially available nutrients that are required for plant growth.

Additional key words: Acid soils, metals, plant nutrients.

Introduction

Reclaiming soils that are heavily contaminated with elemental sulphur is specific to a small part of the oil and gas industry. Alberta produces 95% of Canada's elemental sulphur by converting the hydrogen sulphide present in sour oil and gas to elemental sulphur (Hyne 1977).

The majority of sour gas plants built prior to the mid 1970's stored elemental sulphur by pouring molten sulphur into a large block. The block was poured on top of a basepad, which was also usually formed from molten sulphur. Many of the basepads were poured directly onto soil, with minimal ground preparation.

There are approximately 105 block basepads at 34 locations in western Canada (Hyne and Schwalm 1983). These basepads range from a few hundred to fifty thousand square meters in area (Hyne 1986). Since 1980 few, if any, new basepads have been established in western Canada.

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The clean-up and reclamation of former sulphur block basepad sites can be a difficult process. As much as 30% sulphur may remain in the soil once the initial clean-up phase is completed. Little information is available about the biological, chemical and physical condition of soils underlying basepads. Data collected to date indicate that the soils can be highly acidified and that large amounts of sulphate-sulphur can accumulate and be leached into the underlying soils (Leitch and Nyborg 1985). The effect of sulphur contamination on the quality of leachate produced from soils was studied in a greenhouse experiment to determine if there were any related environmental and health risks potentially associated with these soils.

The leachate trials outlined in this paper were conducted as part of a larger experiment that investigated the effects of sulphur contamination in soil and evaluated the reclamation effectiveness of particular amendments on these soils (Leggett 1987, Leggett and Parkinson 1988).

Materials and Methods

Experimental Set-up

Soil for a greenhouse experiment was taken near a sour gas plant located in south-central Alberta. Sulphur-contaminated soil was removed from the 0-15 cm deep zone below a freshly exposed portion of the basepad. This soil had a total sulphur concentration of 14%. The control soil came from the same zone depth of a farmer's field located northwest of the gas plant. The control soil was from the same soil map unit as the contaminated soil, had a neutral pH and contained less than 0.1% total sulphur.

Different levels of sulphur were obtained by mixing proportions of contaminated and uncontaminated soils together. The final total sulphur concentrations of the soils used in the experiment were less than 0.1% (control), 4%, 9% and 14%. For each sulphur level the reclamation treatments were no treatment, treatment with limestone ($CaCO_3$) at a rate of three times the detected sulphur, treatment with both $CaCO_3$ and cattle manure (at a rate equivalent to 40 tonnes/ha) and treatment with cattle manure only. Agricultural limestone containing less than 5% $MgCO_3$ was used.

Sixteen pots comprised one replicate (4 sulphur levels x 4 treatments). There were 5 replicates in each trial for a total of 80 pots. Each pot contained 3500g of soil plus amendments, and was planted with reed canary grass.

Leachate Collection

At initiation and completion of the growth trial all pots were watered, by weight, to approximately field capacity plus 150 g. Leachate was collected by draining excess water into collection containers. Selected subsamples from the second leachate trial were acidified for metal analyses (aluminum, iron and manganese).

The pH and conductivity measurements were taken immediately following collection and filtration. The nitrate- and ammonium-nitrogen, phosphate-phosphorous and sulphate-sulphur concentrations of the filtrates were determined using a Technicon II Auto Analyzer. Samples were either analyzed within 48 hours of collection or frozen for analysis at a future date.

All data were tested for significance with a two-way analysis of variance and the Scheffe multiple range test. The accepted level of significance for all tests was $p < 0.05$. Values presented in each table followed by the same letter(s) are not significantly different.

Results

Similar trends in all measured parameters were noted from both leaching trials. Treatment of the soils with manure had no significant effect on any of the parameters measured (Tables 1-7). Leachate produced from unlimed, sulphur-contaminated soils were strongly acidic (Table 1). The pH of leachate generated from control soils were mildly acidic, while the pH of leachate produced from limed, sulphur-contaminated soils were neutral.

Conductivity values were highest in leachate produced from unlimed, sulphur-contaminated soil (Table 2). Within this group, conductivity values increased with increasing sulphur concentration. Leachate from limed, sulphur-contaminated soil were at least ten-fold lower than those from their unlimed counterparts.

Leachate produced from unlimed, sulphur-contaminated soils contained elevated levels of both nitrate- and ammonium-nitrogen (Tables 3 and 4). Nitrate values remained constant as soil sulphur levels increased, whereas ammonium levels increased with increasing soil sulphur concentration. Ammonium-and nitrate-nitrogen in leachate produced from control soils and from limed, sulphur-contaminated soils were not significantly different.

Elevated phosphate-phosphorous levels were found in leachate from unlimed, sulphur-contaminated soils but there was no clear trend with increasing soil sulphur concentration (Table 5). Phosphate concentrations in leachate from limed soils were not significantly different than those from control soils.

Sulphate-sulphur levels were highest in leachate produced from unlimed, sulphur-contaminated soils (Table 6). Limed soils contained the next highest levels, while leachate from control soils had the lowest sulphate concentrations.

Soluble aluminum, iron and manganese in leachate

Unlike other leachate data, metal determinations were made only on selected samples taken following the growth trial. Leachate from manure-treated soils were not analyzed for soluble metals. As only two replicate determinations were made, an analysis of variance was not conducted.

Leachate from unlimed soils contained higher levels of soluble aluminum, iron and manganese than did leachate from control soils (Table 7). Leachate from limed soils contained lower levels of measured soluble metals than did leachate from control soils. Highest levels of metals were recorded from pots containing unlimed 9% sulphur-contaminated soils. Further investigations would be required to determine if this trend is merely a function of low sample replication.

Discussion

The objective of the leaching trials was to chemically characterize the leachate produced from the various soil mixtures. No attempt

TABLE 1. The pH of leachate produced from pot soil used for growth trials. Data are means (n=5) ± standard deviations.

Soil Sulphur (%)	Reclamation Treatments No Treatment	Limestone	Limestone and Manure	Manure
a) Prior to growth trial				
<0.1	5.3 ± 1.0^{bc}	4.6 ± 1.2^{b}	5.1 ± 0.9^{bc}	5.8 ± 1.0^{bc}
4	1.7 ± 0.2^{a}	7.2 ± 0.3^{c}	6.8 ± 0.7^{c}	1.8 ± 0.1^{a}
9	0.9 ± 0.2^{a}	7.0 ± 0.2^{c}	6.9 ± 0.3^{c}	0.9 ± 0.1^{a}
14	0.5 ± 0.1^{a}	6.9 ± 0.2^{c}	7.1 ± 0.1^{c}	0.5 ± 0.1^{a}
b) Following growth trial				
<0.1	4.9 ± 0.7^{b}	5.0 ± 0.2^{b}	5.5 ± 0.5^{b}	5.3 ± 0.3^{b}
4	1.3 ± 0.4^{a}	7.1 ± 0.4^{c}	$7.3+0.1^{c}$	1.4 ± 0.2^{a}
9	1.0 ± 0.1^{a}	7.3 ± 0.2^{c}	$7.4+0.1^{c}$	1.0 ± 0.1^{a}
14	0.7 ± 0.1^{a}	7.5[1]	7.5 ± 0.1^{c}	0.7 ± 0.2^{a}

TABLE 2. Electrical conductivity (mS cm^{-1}) of leachate produced from pot soil used for growth trials. Data are means (n=5) + standard deviations.

Soil Sulphur (%)	Reclamation Treatments No Treatment	Limestone	Limestone and Manure	Manure
a) Prior to growth trial				
<0.1	1.4 ± 0.7^{a}	1.2 ± 0.3^{a}	0.9 ± 0.4^{a}	1.2 ± 0.3^{a}
4	33 ± 5.1^{c}	3.2 ± 0.1^{b}	3.4 ± 0.1^{b}	32 ± 5.0^{c}
9	74 ± 18^{d}	3.5 ± 0.2^{b}	3.8 ± 0.2^{b}	71 ± 13^{d}
14	141 ± 21^{e}	3.1 ± 0.4^{b}	4.4 ± 0.2^{b}	143 ± 14^{e}
b) Following growth trial				
<0.1	0.6 ± 0.3^{a}	0.7 ± 0.3^{a}	0.5 ± 0.3^{a}	0.7 ± 0.3^{a}
4	47 ± 8^{c}	3.2 ± 0.4^{b}	$3.3+0.2^{b}$	42 ± 4^{c}
9	61 ± 10^{c}	3.5 ± 0.2^{b}	3.7 ± 0.2^{b}	58 ± 5^{c}
14	108 ± 22^{d}	2.58[1]	3.9 ± 0.4^{b}	124 ± 22^{d}

[1] n = 1

TABLE 3. NO_3-N (ug ml^{-1}) in leachate produced from pot soil used for growth trials. Data are means (n=5) ± standard deviations.

	Reclamation Treatments			
Soil Sulphur (%)	No Treatment	Limestone	Limestone and Manure	Manure
a) Prior to growth trial				
<0.1	30 ± 14^{bc}	42 ± 22^{c}	21 ± 10^{bc}	15 ± 7^{bc}
4	291 ± 39^{d}	17 ± 7^{bc}	19 ± 6^{bc}	418 ± 85^{d}
9	408 ± 73^{d}	10 ± 4^{b}	11 ± 4^{bc}	398 ± 95^{d}
14	660 ± 74^{d}	2 ± 2^{a}	8 ± 2^{b}	618 ± 87^{d}
b) Following growth trial				
<0.1	$0.4\pm0.3^{1,a}$	$11\pm4^{2,b}$	ND	$0.2\pm0.2^{2,a}$
4	473 ± 84^{c}	$0.5\pm0.1^{1,a}$	0.7 ± 0.5^{a}	578 ± 119^{c}
9	522 ± 119^{c}	0.8 ± 0.4^{a}	0.4 ± 0.2^{a}	515 ± 107^{c}
14	674 ± 104^{c}	ND	1 ± 2^{a}	706 ± 151^{c}

TABLE 4. NH_4-N (ug ml^{-1}) in leachate produced from pot soil used for growth trials. Data are means (n=5) ± standard deviations.

	Reclamation Treatments			
Soil Sulphur (%)	No Treatment	Limestone	Limestone and Manure	Manure
a) Prior to growth trial				
<0.1	0.5 ± 0.2^{ab}	0.5 ± 0.1^{ab}	0.4 ± 0.2^{a}	0.4 ± 0.2^{a}
4	574 ± 68^{c}	0.8 ± 0.3^{ab}	1.3 ± 0.4^{ab}	861 ± 162^{cd}
9	1177 ± 384^{d}	1.4 ± 0.3^{ab}	1.9 ± 0.3^{b}	1264 ± 317^{d}
14	1841 ± 238^{d}	1.1 ± 0.6^{ab}	1.9 ± 1.0^{b}	1668 ± 241^{d}
b) Following growth trial				
<0.1	0.5 ± 0.3^{a}	0.5 ± 0.2^{a}	$0.6\pm0.2^{1,a}$	0.4 ± 0.2^{a}
4	925 ± 110^{b}	0.3 ± 0.1^{a}	0.4 ± 0.3^{a}	1034 ± 164^{bc}
9	1275 ± 213^{bc}	0.5 ± 0.1^{a}	0.4 ± 0.2^{a}	1548 ± 173^{bc}
14	1729 ± 284^{c}	0.2^{3}	0.7 ± 0.5^{a}	2065 ± 373^{c}

1	n=3
2	n=2
3	n=1
ND	Not determined

TABLE 5. PO_4-P (ug ml^{-1}) in leachate produced from pot soil used for growth trials. Data are means (n=5) ± standard deviations.

Soil Sulphur (%)	Reclamation Treatments No Treatment	 Limestone	 Limestone and Manure	 Manure
a) Prior to growth trial				
<0.1	0.2 ± 0.1^{a}	0.1 ± 0.1^{a}	0.6 ± 0.2^{a}	0.4 ± 0.1^{a}
4	53 ± 16^{b}	0.4 ± 0.1^{a}	0.6 ± 0.1^{a}	72 ± 56^{b}
9	169 ± 40^{c}	0.5 ± 0.1^{a}	0.7 ± 0.1^{a}	225 ± 36^{c}
14	116 ± 25^{bc}	0.5 ± 0.1^{a}	0.7 ± 0.1^{a}	183 ± 47^{c}
b) Following growth trial				
<0.1	0.2 ± 0.2^{a}	0.1 ± 0.1^{a}	$0.4\pm0.2^{1,a}$	0.3 ± 0.2^{a}
4	96.6^{2}	0.1 ± 0.1^{a}	0.3 ± 0.1^{a}	123 ± 22^{c}
9	161 ± 24^{cd}	0.2 ± 0.1^{a}	0.3 ± 0.1^{a}	232 ± 37^{d}
14	78 ± 17^{b}	0.3^{2}	0.4 ± 0.1^{a}	147 ± 34^{c}

TABLE 6. SO_4-S (mg ml^{-1}) in leachate produced from pot soil used for growth trials. Data are means (n=5) ± standard deviations.

Soil Sulphur (%)	Reclamation Treatments No Treatment	 Limestone	 Limestone and Manure	 Manure
a) Prior to growth trial				
<0.1	0.7 ± 0.4^{ab}	$.47\pm.18^{b}$	$.43\pm.31^{a}$	$.59\pm.26^{1,ab}$
4	38.1 ± 10.8^{c}	1.6 ± 0.1^{b}	1.6 ± 0.1^{b}	37.4 ± 8.1^{c}
9	82.0 ± 26.5^{c}	1.5 ± 0.1^{b}	1.6 ± 0.1^{b}	81.7 ± 12.6^{c}
14	90.7 ± 11.7^{c}	1.4 ± 0.3^{b}	1.6 ± 0.1^{b}	55.8 ± 23.8^{c}
b) Following growth trial				
<0.1	$0.3\pm0.2^{1,a}$	0.3 ± 0.1^{a}	$0.5\pm0.3^{2,a}$	0.3 ± 0.2^{a}
4	$50.9\pm26.2^{3,c}$	2.3 ± 0.2^{b}	2.4 ± 0.1^{b}	$77.6\pm11.6^{2,c}$
9	85.5 ± 5.8^{c}	2.4 ± 0.3^{b}	2.6 ± 0.2^{b}	82.5 ± 22.9^{c}
14	67.2 ± 7.8^{c}	ND	3.1 ± 0.6^{b}	63.9 ± 16.2^{c}

1 n=4
2 n=3
3 n=2
ND Not determined

TABLE 7. Soluble aluminum, iron, and manganese (ug ml^{-1}) in leachate produced from selected pot soil used for growth trials. Data are means (n=2) ± standard deviations.

Soil Sulphur (%)	Metal Measured	Reclamation Treatments No Treatment	Limestone	Limestone and Manure	Manure
<0.1	Al	0.12±0.11	ND	ND	ND
	Fe	0.73±0.44			
	Mn	0.03±0.01			
4	Al	778±3	0.01±0.01	ND	ND
	Fe	4817±1439	0.12±0.04		
	Mn	514±34	0.01±0.01		
9	Al	1082±293	0.01±0.00	ND	ND
	Fe	8220±3224	0.12±0.04		
	Mn	419±169	0.01±0.01		
14	Al	526±163	0.01[1]	ND	ND
	Fe	2554±1055	0.02[1]		
	Mn	13.8±5.7	0.18[1]		

1 n=1
ND Not determined

was made to relate plant nutrient concentrations in leachate with those measured in the soils.

Acidic leachate were produced from all unlimed, sulphur-contaminated pots, while leachate from limed pots were neutral. The two highest sulphur levels resulted in pH values of less than 1.0.

Sulphate-sulphurconcentrations occurred in acidic leachate in levels as high as 91 mg/ml while concentrations in leachate from limed soils ranged up to 26 mg/ml. Conductivity values were greater in leachate from unlimed soils than in those from control or limed soils. The increase in soluble salts present in acidic leachate was likely due to the presence of high levels of sulphate salts. High levels of other nutrients, such as nitrogen and phosphorous, were also present in acidic leachate. In contrast, amounts of nitrogen and phosphorous leached from limed soils were not significantly higher than those from control soils. The use of manure as a reclamation amendment appeared to be ineffective in mitigating the effects of soil acidification such as the leaching of metals and nutrients.

Soluble aluminum, iron and manganese concentrations in leachate produced from limed soils were well below 1 ug/ml, while concentrations in the acidic leachate were recorded in the hundreds of ug/ml. These results indicate the potential for metal contamination from sulphur-contaminated soils that are not limed immediately following basepad removal. Leaving a soil that is heavily contaminated with elemental sulphur exposed and unlimed is not only a potential health hazard as a result of the metal concentrations that could potentially reach the groundwater, but also a drain of potentially available nutrients that are required for plant growth.

The results obtained in this study suggest that leachate from limed, sulphur-contaminated soils would not present a hazard to local groundwater supplies but acidic leachate from unlimed, sulphur-contaminated soils may contaminate groundwater. This study indicates that soils acidified as a result of elemental sulphur contamination require rapid neutralization in order to prevent formation of acidic leachate.

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EFFECTS OF PHOSPHATIC AMENDMENTS ON YIELD AND ELEMENTAL COMPOSITION OF CORN GROWN ON ACID MINESOILS[1]

by

J. C. Sencindiver and D.K. Bhumbla[2]

Abstract. Greenhouse experiments were conducted to evaluate the growth and chemical composition of three crops of corn grown on limed and unlimed minesoils amended with phosphatic clay, rock phosphate, and monocalcium phosphate. Application rates of phosphatic clay and rock phosphate were 288 and 576 mg P kg^{-1}. Phosphatic clay also was added at 1152 mg P kg^{-1}. Monocalcium phosphate was added at 50 mg P kg^{-1}, and a control had no phosphate amendment. Corn yields were higher on phosphatic clay-treated minesoils than on minesoils treated with rock phosphate or monocalcium phosphate. Yields were generally no better for the highest application rate than they were for the middle rate of phosphatic clay. Phosphatic clay improved the uptake of macronutrients by corn growing on both limed and unlimed minesoils. Concentrations of calcium and phosphorus were significantly higher in tissues of plants grown on phosphatic-clay treated minesoils than on minesoils with other treatments. Tissue concentrations of manganese decreased with increasing levels of phosphatic amendments.

Additional Key Words: rock phosphate, phosphatic clay, abandoned mine lands, amendments.

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Introduction

In 1980 the U.S. Office of Surface Mining reported that 37,070 hectares (91,600 acres) of abandoned mine land (AML) and waste banks (refuse or gob piles) in West Virginia required some reclamation (OSMRE, 1980). The report also stated that an additional 189,955 hectares (469,000 acres) across the United States needed to be reclaimed.

Poor stands of vegetation on these AML sites may be related to steep slopes, coarse texture or particle size, acidity, and/or low fertility. Studies have shown that phosphorus is one of the most limiting plant nutrients in minesoils (Dant, 1984). Other studies have shown that phosphate will help to control formation of acidity by reducing pyrite oxidation (Renton et al., 1988). Therefore, phosphorus fertilizer in various forms, including rock phosphate, is normally added as an amendment to minesoils.

Phosphatic clay, a waste product of the Florida phosphate industry, has properties that may be able to correct fertility, acidity and water retention problems of AML. Therefore, the objective of this study was to evaluate the effects of phosphatic clay applied to abandoned minesoils on the growth of corn (*Zea mays*).

Materials and Methods

Minesoil Description

Minesoils used in this study were collected from two sites in Monongalia County, West Virginia. The Lower Kittanning coal had been mined at one site 30 or more years before this study. Shale was the predominant rock type. Upper Freeport coal had been mined at the other site approximately 15 years before this study. The predominant rock type on this site was sandstone. Neither site had been reclaimed, and the spoils were left in mounds with steep side-slopes. The minesoils developing on these sites were classified as loamy-skeletal, mixed, acid, mesic Typic Udorthents (Soil Survey Staff, 1975).

Bulk surface (0-20 cm) soil samples were collected from barren areas at each site. They were air-dried, passed through a #10 mesh (2 mm) screen, and analyzed for basic soil properties (Table 1).

Soil Analyses

Lime requirement of the minesoils was determined by the five-minute boiling method using $Ca(OH)_2$ (Sobek et al., 1978). Soil exchangeable acidity and aluminum was extracted by KCl (Yuan, 1959). Exchangeable Ca, Mg, and K were extracted by 1 *N*, neutral ammonium acetate (Soil Survey Staff, 1972). Exchangeable cations were analyzed by atomic absorption spectrophotometry using standard methods. Cation exchange capacity of the soils was computed from the summation of exchangeable bases and exchangeable acidity. Organic carbon was determined by wet oxidation with acid dichromate (Soil Survey Staff, 1972). Copper, Zn, Mn, and Fe were determined by the DTPA method (Lindsay and Norvell, 1978). Total sulfur was analyzed on an automated sulfur analyzer. Soil pH was measured in a 1:1 soil:water suspension. Total phosphorus of the phosphatic clay was determined by the sodium carbonate fusion method (Lim and Jackson, 1982). Particle size distribution was determined by the pipette method (Soil Survey Staff, 1972).

Table 1 -- Chemical and physical properties of minesoils and phosphatic clay used in greenhouse experiments.

		Materials		
Properties	Units	Sandstone Minesoil	Shale Minesoil	Phosphatic Clay
pH	--	4.03	3.74	7.5
Organic Carbon	%	0.05	1.01	0.3
CEC	meq/100 g	8.50	9.51	37.6
Exchangable Cations	meq/100 g			
Ca^{++}		3.54	1.02	17.4
Mg^{++}		0.79	0.52	10.2
K^{+}		0.05	0.15	0.3
Al^{+++}		1.63	4.00	ND
Extractable Metals	ppm			
Zn		2.24	8.54	6.0
Cu		0.44	3.56	2.7
Mn		57.20	42.60	1.0
Fe		28.50	60.10	57.7
Particle Size Distribution	%			
sand		68.50	22.60	8.1
silt		21.60	55.70	17.2
clay		9.90	21.70	74.6
Total Elements	%			
S		0.54	0.03	--
P		--	--	2.4
Lime Requirement	mg/1000 mg	2.50	12.50	--

Greenhouse Study

Greenhouse experiments were conducted in a randomized complete block design with three replications of seven treatments. Three weeks before the initiation of the experiment, 2.5 kg of soil were allocated to each of 84 polyethylene-lined plastic pots. Soil in one-half of the pots from each site was treated with $Ca(OH)_2$ to meet the lime requirement (Table 1). All soils were incubated through three wetting and drying cycles. Each wetting and drying cycle consisted of adding 500 ml of water to each pot and allowing the pots to dry for one week. At the end of the third drying cycle the soil was taken out of the pots and bulked in the following four lots: shale unlimed, shale limed, sandstone unlimed, and sandstone limed. The soils were mixed thoroughly and repotted. The following treatments were applied to both the unlimed and limed minesoils:

1. control - no P
2. 50 ppm P as $Ca_2(H_2PO_4)_2$ - monocalcium phosphate
3. 0.3% rock phosphate (RP-1)[1]
4. 0.6% rock phosphate (RP-2)
5. 1.2% phosphatic clay (PC-1)[2]
6. 2.4% phosphatic clay (PC-2)
7. 4.8% phosphatic clay (PC-3)

The amount of rock phosphate and phosphatic clay were calculated on a weight basis. The phosphorus contents of rock phosphate and phosphatic clay were 9.6 and 2.4 percent, respectively (Tables 1 and 2). Thus the amount of phosphorus supplied by 1.2% phosphatic clay was the same as that supplied by 0.3% rock phosphate. The phosphatic materials used in this study were ground to pass through a 60-mesh (0.25 mm) sieve. Every pot in these experiments received 50 ppm K as KCl, 67 ppm N as NH_4NO_3, and 5 ppm Zn as $ZnSO_4$.

Table 2 -- Total elemental analysis of rock phosphate used in greenhouse studies.

Element	Units	Rock Phosphate
P	%	9.60
K	%	0.94
Ca	%	20.72
Mg	%	0.53
Al	%	1.02
Fe	%	1.20
Zn	ppm	108.00
Cu	ppm	15.00
Mn	ppm	227.00

Seven seeds of corn (Zea mays) were planted in each pot. One week after germination, plants in each pot were thinned to four uniform plants.

All treatments within each soil were randomized within each block and watered with distilled and deionized water. Plants were watered as needed to prevent wilting. Corn was harvested 8 weeks after seeding. The aboveground plant material was washed with distilled and deionized water and oven-dried at 70°C for 48 hours. The plants were weighed and dry matter yields were recorded. Samples were then ground in a micro-Wiley mill in preparation for elemental analyses.

Soil was removed from each pot and crushed to separate roots. Roots were removed, and soil samples from each pot were collected. Soils from the three replications of each treatment were thoroughly mixed and redivided into three pots for subsequent corn crops. All soil samples were air dried, pulverized, and stored for analysis. Data for these post-harvest minesoils are presented elsewhere (Bhumbla and Sencindiver, 1989).

Two additional crops of corn were

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[1] Rock phosphate was supplied by Texasgulf Chemical Company, Aurora, NC.

[2] Phosphatic clay was supplied by Agrico Mining Company, Bartow, FL.

grown on the same soils, and plant and soil samples were obtained in the same manner as described for the first crop. Both second and third crops received additions of N, K and Zn fertilizers at the levels applied to the first crop. No data for the second or third crops are presented in this paper, but they were presented in an earlier report (Bhumbla and Sencindiver, 1989).

Plant Analyses

Calcium, Mg, K, P, Zn, and Mn concentrations in plant tissue were determined by the following method: 1.0 g of ground plant tissue was digested with a mixture of HNO_3 and $HClO_4$ (3:1) in a tall 200-ml beaker in a perchloric acid hood. The digested residue was dissolved in 50 ml of 0.1 N HCl. Phosphorus was determined by the molybdivanadophosphoric acid method outlined by Kitson and Mellon (1944). Optical density was read at 470 mu. Calcium, Mg, K, Zn, and Mn were determined with a Perkin Elmer model 5000 atomic absorption spectrophotometer.

Results and Discussion

Plant Dry Matter Yield

In phosphate-treated unlimed sandstone minesoil, the highest yields were recorded for the phosphatic clay treatments (Table 3). Among the phosphate treatments, monocalcium phosphate had the lowest yield. Phosphatic clay increased the yield of the first corn crop by over seven times the yield of the control. The application of phosphatic clay at the first level produced significantly higher dry matter than that produced by rock phosphate.

When sandstone minesoil was limed, but had no phosphorus added, the yield of the first corn crop increased from 1.5 g pot^{-1} to 1.76 g pot^{-1} (Table 3). The yield increase

Table 3 -- Effect of phosphate treatments on dry matter yields of corn crops grown on limed and unlimed sandstone and shale minesoils.

	Sandstone		Shale	
Phosphate Treatments	Unlimed Corn Crop 1	Limed Corn Crop 1	Unlimed Corn Crop 1	Limed Corn Crop 1
	g pot^{-1}			
Control	1.50	1.76	1.70	2.60
Monocalcium phosphate	5.80	9.70	8.30	9.60
Rock phosphate - 1	8.50	2.70	9.90	8.70
Rock phosphate - 2	10.20	3.40	12.50	8.50
Phosphatic clay - 1	10.60	6.70	13.20	8.33
Phosphatic clay - 2	11.10	8.00	13.90	10.20
Phosphatic clay - 3	11.60	10.60	14.90	10.40
LSD (0.05)	0.75	0.97	0.75	2.17

for unlimed sandstone with the application of monocalcium phosphate was from 1.50 g pot^{-1} to 5.80 g pot^{-1}. These data indicate that phosphorus was a limiting element for crop growth in the minesoil under investigation. When lime was supplemented with phosphorus, e.g., addition of monocalcium phosphate to limed sandstone, the yield increased from 1.76 g pot^{-1} to 9.70 g pot^{-1}. Phosphatic clay-treated limed sandstone minesoil produced about two times the dry matter produced in rock phosphate-treated limed sandstone. Application of lime reduced the dry matter yields in rock phosphate-treated minesoils (Table 3). This reduction in dry matter yield was due to reduced rock phosphate dissolution in the high calcium and high pH environment of limed sandstone. Trends for the shale minesoil (Table 3) were similar to the trends for the sandstone minesoil.

Plant Concentrations of Nutrients

Calcium and Phosphorus. The highest concentrations of calcium were observed in plants grown on the sandstone control (Table 4), but the lowest phosphorus concentrations were observed on the same treatment (Table 5). These high levels of calcium in the plant tissue were related to stunted plant growth. These data seem to indicate that the most limiting nutrient for plant growth was phosphorus. In the shale control for corn, plant calcium concentration was 2.3 g kg^{-1} (Table 4). When the minesoil was limed, the corresponding calcium concentration was 7.3 g kg^{-1}. Therefore, liming resulted in a 3.5-fold increase in calcium concentration, translating into a yield increase of 0.9 g (Table 3). When phosphorus concentrations in plant tissue were raised by addition of phosphatic clay from 1.20 to 4.35 g

Table 4 -- Effect of phosphate treatments on concentrations of calcium in plant tissue of corn grown on limed and unlimed shale and sandstone minesoils.

	Sandstone		Shale	
Phosphate Treatments	Unlimed Corn Crop 1	Limed Corn Crop 1	Unlimed Corn Crop 1	Limed Corn Crop 1
	---g kg^{-1}---			
Control	7.6	8.4	2.3	7.3
Monocalcium phosphate	2.4	4.0	2.4	5.7
Rock phosphate - 1	2.5	4.1	3.2	5.3
Rock phosphate - 2	2.8	4.8	2.6	4.8
Phosphate clay - 1	4.9	4.2	2.6	4.7
Phosphate clay - 2	5.0	4.2	4.0	4.8
Phosphate clay - 3	5.0	4.3	3.4	4.9
LSD (0.05)	0.3	0.3	0.6	0.5

Table 5 -- Effect of phosphate treatments on concentrations of phosphorus in plant tissue of corn grown on limed and unlimed shale and sandstone minesoils.

	Sandstone		Shale	
Phosphate Treatments	Unlimed Corn Crop 1	Limed Corn Crop 1	Unlimed Corn Crop 1	Limed Corn Crop 1
	------------------g kg^{-1}-------------------			
Control	1.20	2.40	1.20	1.80
Monocalcium phosphate	2.25	1.80	3.60	4.65
Rock phosphate - 1	3.30	3.06	4.65	4.20
Rock phosphate - 2	3.45	3.30	5.25	3.90
Phosphatic clay - 1	3.45	2.55	4.35	3.30
Phosphatic clay - 2	3.75	2.85	3.70	3.60
Phosphatic clay - 3	3.90	2.55	3.90	3.90
LSD (0.05)	0.17	0.32	0.45	0.62

kg^{-1} (Table 5), the corresponding crop yield increase was 11.5 g (Table 3).

Manganese and Zinc. Manganese concentrations decreased with increases of phosphatic amendments (Table 6). The lowest plant tissue manganese concentrations were observed in phosphatic clay-treated soils. Phosphorus fertilizers are reported to increase the level of soil-solution manganese in most soils, probably because of acidic reaction of dissolved superphosphate or because of acidity produced by the nitrification of ammonium phosphate (Heintze, 1969). The decreased soil pH associated with high phosphorus rates was considered to be responsible for increased manganese uptake (Smilde, 1973).

There were two important reasons for the observed manganese depression by the phosphatic amendments. The amendments used in the present study had tribasic phosphates, so the applied phosphatic amendments were a sink for hydrogen ions. Soil solution concentrations of Mn^{2+}, as well as exchangeable Mn^{2+}, are governed by the solubilities of manganese oxides such as Mn_2O_3 and MnO_2 (Adams, 1980). Manganese from its (+4) and (+3) oxidation state can be reduced to (+2) oxidation state by ferrous ions (Jaurequi and Reisenauer, 1982). In the present study manganese reduction was controlled effectively by reducing the rate of ferrous iron production from pyrite oxidation. The formation of insoluble manganese phosphates was also responsible for the observed decrease in manganese concentration in plants with increasing phosphorus application.

There were significant differences in zinc concentrations in tissue of plants grown on minesoils (Table 7). The classic phosphorus-zinc interaction was observed. Increasing levels of phosphorus

Table 6 -- Effect of phosphate treatments on concentrations of manganese in plant tissue of corn grown on limed and unlimed shale and sandstone minesoils.

	Sandstone		Shale	
Phosphate Treatments	Unlimed Corn Crop 1	Limed Corn Crop 1	Unlimed Corn Crop 1	Limed Corn Crop 1
	mg kg^{-1}			
Control	2950	1637	265	183
Monocalcium phosphate	550	927	253	166
Rock phosphate - 1	670	676	245	123
Rock phosphate - 2	525	632	238	114
Phosphatic clay - 1	630	534	207	95
Phosphatic clay - 2	298	328	228	104
Phosphatic clay - 3	195	207	155	115
LSD (0.04)	121	111	74	27

Table 7 -- Effect of phosphate treatments on concentrations of zinc in plant tissue of corn grown on limed and unlimed shale and sandstone minesoils.

	Sandstone		Shale	
Phosphate Treatments	Unlimed Corn Crop 1	Limed Corn Crop 1	Unlimed Corn Crop 1	Limed Corn Crop 1
	mg kg^{-1}			
Control	290	299	218	73
Monocalcium phosphate	110	180	125	53
Rock phosphate - 1	110	75	120	48
Rock phosphate - 2	75	55	83	42
Phosphatic clay - 1	75	52	92	40
Phosphatic clay - 2	60	34	74	36
Phosphatic clay - 3	54	35	67	34
LSD (0.05)	9	13	7	7

resulted in decreasing zinc concentrations in plant tissues. Similar observations of the phosphorus-zinc interaction have been reported by other researchers (Stukenholtz et al., 1966).

Conclusions

Phosphatic clay has potential for amending acid minesoils for revegetation purposes. Corn yields were higher on phosphatic clay-treated minesoils than on the same minesoils treated with rock phosphate or monocalcium phosphate. Yields were generally no better for the highest level (4.8% by weight) than they were for the second level (2.4% by weight) of phosphatic clay treatments. Phosphatic clay is a better amendment for unlimed than limed minesoils. Liming of both sandstone and shale minesoils prior to application of phosphatic clay or rock phosphate generally reduced yields.

Phosphatic clay improved the uptake of macronutrients of plants growing on both minesoils. Concentrations of Ca and P were significantly higher in the tissue of plants grown on the phosphatic clay-treated minesoils than on minesoils with other treatments.

When compared to the control, phosphate treatments significantly reduced the plant concentrations of Mn and Zn. However, differences between phosphatic clay treatments and other phosphate treatments were not always significant.

It appears that the second level of phosphatic clay additions (2.4% by weight) would be the most practical application. This application rate of phosphatic clay was generally better than an equivalent rate (based upon phosphorus content) of rock phosphate.

The overall conclusion of this study is that phosphatic clay is a better revegetation amendment on acid minesoils than rock phosphate. Differences between the effects of rock phosphate and phosphatic clay are related to surface area. All particles of phosphatic clay are less than 2 mm in diameter and 75% of those particles are less than 0.002 mm. The rock phosphate was ground to less than 60 mesh (0.25 mm), but most of the material was sand size (> 0.05 mm). Since this study was conducted in a greenhouse, these results need to be confirmed in a field experiment before they can be recommended for use in revegetation of mined lands.

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UTILISATION DE SUBSTANCES ORGANIQUES À DES FINS DE MISE EN VÉGÉTATION DE REJETS MINIERS ACIDES[1]

Par

Antoine Karam et Louis M. Azzaria[2]

Abstract. There are advantages to the revegetation of the tailings of the abandoned East Sullivan mine in Val d'Or, Québec, Canada. However, the tailings constitute a medium that is unfavorable to plant growth. They are highly acid, have a high iron sulphides content, and a low level of organic matter and major nutrients. Greenhouse experiments were carried out in order to evaluate the effect of the addition of septic tank sludge and wood chips on the chemical characteristics of the tailings and the growth of five plant species. A good growth of red fescue, timothy, birdsfoot trefoil, and corn was established on acid mine tailings when a combination of the organic amendments, lime and fertilizer was applied. The organic amendments incorporated to a depth of 10 cm contribute to increasing the pH of the tailings and their effluent.

ADDITIONAL KEY WORDS: Pollution; heavy metals; septic tank sludge; wood chips.

INTRODUCTION

Le parc à résidus miniers d'East Sullivan Mines Ltd est situé dans le canton de Bourlamarque en Abitibi, Québec, à environ 7 kilomètres au sud-est de la ville de Val d'Or. Le parc qui occupe une superficie de 122 hectares, a un potentiel d'acidification et de mise en solution des métaux pouvant affecter certains cours d'eau et lacs du secteur. Les métaux lourds lessivés des résidus miniers acides du site East Sullivan sont par ordre décroissant: le fer, le manganèse et le cuivre Le Groupe Conseil Planigram 1987).

Depuis 1984, trois usines déposent des déchets provenant de la transformation du bois sur le parc. La ville de Val d'Or dépose, depuis 1985, les boues de la station municipale d'épuration des eaux usées sur le parc à résidus miniers. De plus, ce dernier reçoit des boues de fosses septiques ainsi que des déchets d'origine industrielle. Les résidus forestiers sont déposés et étendus sur le parc dans le but de l'isoler de l'eau de précipitation et de l'air ambiant tandis que les boues servent à amender la surface des résidus forestiers afin d'y implanter la végétation.

Le succès de l'établissement d'une végétation sur les résidus miniers acides repose sur plusieurs facteurs tels l'ajustement du pH, la disponibilité des éléments nutritifs surtout l'azote et la sélection de plantes rustiques adaptées aux conditions adverses du milieu (Bennett 1977; Lundberg et al. 1977; McNeilly et Johnson 1978; Paquet 1984). Toutefois, l'utilisation de matériaux organiques pourrait constituer un moyen susceptible d'amender la surface des parcs à résidus miniers (Holmberg 1980).

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Le but de la présente étude est d'examiner l'incidence de l'apport aux rejets miniers acides de substances organiques (boues de fosses septiques et sciure de bois) sur: 1) La croissance de la fétuque rouge et de la fléole des prés; 2) Les caractéristiques chimiques desrejets miniers et leur effluent.

Méthodologie expérimentale

Matériaux

Les résidus miniers utilisés dans la présente étude proviennent de douze sites d'échantillonnage couvrant l'ensemble du parc à résidus miniers East Sullivan. Ces échantillons ont été intimement mélangés pour former un échantillon composite.

Les divers amendements organiques utilisés dans la présente étude sont: 1) les boues de fosses septiques de la firme Les Fosses Septiques du N.O. Inc. à Val d'Or, et 2) les résidus forestiers (sciure de bois).

Quatre plantes fourragères ont été sélectionnées pour être implantées dans les résidus miniers acides, ce sont la fétuque rouge traçante, la fléole des prés cv Climax, le lotier corniculé cv Léo et le maïs-ensilage cv Pioneer.

Essais de fertilisation

L'échantillon composite de résidus miniers acides a été séché à l'air avant d'être mis dans des pots de plastique.

Le dispositif expérimental pour la fétuque rouge et la fléole des prés comprenait 12 traitements répétés 2 fois pour un total de 24 pots par culture (3 doses de boues de fosses septiques x 4 doses de sciure de bois x 2 répétitions). Le tableau 1 résume les différents traitements.

Les milieux de croissance ont reçu, dans tous les pots, des quantités de chaux (carbonate de calcium, qualité analytique) et de fertilisant commercial (17-17-17) correspondant à 4,77 t/ha et 795 kg/ha, respectivement. La quantité de chaux était très inférieure à celle utilisée par plusieurs chercheurs (Paquet 1984; Cescas 1987) dans des études semblables.

Tableau 1. Doses de matériaux organiques utilisées lors des essais de fertilisation

No de traitements	Sciure de bois (SB) (g/pot)	Boues de fosses septiques (BFS) (g/pot)
1	0	0
2	75	0
3	150	0
4	300	0
5	0	75
6	75	75
7	150	75
8	300	75
9	0	150
10	75	150
11	150	150
12	300	150

Une semaine après l'addition de matériaux organiques, de chaux et d'engrais, chaque pot a reçu plusieurs graines de fléole des prés ou de fétuque rouge. La période de croissance (environ 19 semaines) a débuté le 18 juillet 1988 et la récolte a eu lieu le 25 novembre 1988. Les répétitions ont été réparties en blocs aléatoires et les traitements distribués au hasard sur des tables dans la serre. La température dans la serre variait de 22° à 25° C, sous un éclairage aux tubes fluorescents de 16 h/jour.

Les parties aériennes des plants ont été récoltées en coupant à 1 cm environ au-dessus du sol; elles ont été séchées à 70° C pendant 72 h et la matière sèche a été obtenue par pesée. Ceci donnait le rendement en matière sèche lequel est l'indice de la croissance des végétaux. Le matériel végétal séché à 70° C été broyé à 1 mm et le produit broyé fut soumis à la digestion humide en utilisant les acides nitrique et perchlorique concentrés.

Les métaux lourds (Al, Cu, Fe, Mn et Zn) ont été dosés dans les extraits par spectrophotométrie d'absorption atomique.

Essais de lixiviation

Des colonnes de lixiviation de 10 cm de diamètre et 30 cm de longueur furent remplies de 1,96 L de résidus miniers acides (échantillon composite). Les doses d'application et le mode d'incorporation des matériaux organiques apparaissent au tableau 2. On a appliqué et incorporé sur une profondeur de 5 cm l'équivalent de 509 kg/ha d'engrais ayant la formule 0-20-20 pour le lotier corniculé. Les contenus des colonnes réservées à la culture du maïs-ensilage ont reçu des quantités d'engrais à base d'azote, de phosphore et de potassium (46 à 60) selon les doses recommandées par le C.P.V.Q. pour la culture du maïs-ensilage.

Après une semaine d'application de matériaux organiques, de chaux et d'engrais, les colonnes ont été semées avec du lotier corniculé (0,32 g/colonne) ou du maïs-ensilage (2 graines/colonne). La date de semis était le 18 juillet 1988 tandis que les dates de récolte du maïs et du lotier étaient le 3 septembre 1988 et le 18 novembre 1988, respectivement. Les colonnes ont été soumises durant la période de croissance à un arrosage avec 400 ml d'eau distillée selon les besoins de chaque espèce végétative.

Tableau 2. Description des traitements relatifs aux essais de lixiviation de résidus miniers cultivés avec du lotier et du maïs

Identification des traitements	Dose d'application et mode d'incorporation des matériaux organiques
T1	432 cm^3 de BFS + SB ajoutés en surface
T2	432 cm^3 de BFS + SB incorporés sur une profondeur de 5 cm
T3	432 cm^3 de BFS + SB incorporés sur une profondeur de 10 cm
T4	864 cm^3 de BFS + SB incorporés sur une profondeur de 10 cm

Les rendements en matière sèche des parties aériennes ont été mesurés après séchage à l'étuve à 70° C.

Le contenu en métaux lourds des eaux de lixiviation recueillies après le 1^er^ cycle (une semaine après le semis) et le dernier cycle (avant la récolte) de lixiviation a été déterminé par spectrophotométrie d'absorption atomique.

Résultats et discussion

Essais de fertilisation

D'une façon générale, les différentes espèces végétatives se sont bien développées dans les milieux de croissance surtout ceux ayant reçu des matériaux organiques. Toutefois, quelques plants de fétuque rouge ou de fléole des prés ont présenté des symptômes de carences nutritives en azote ou en potassium.

Les productions moyennes en matière sèche pour les différentes espèces cultivées sont présentées dans le tableau 3. L'apport de doses croissantes de boues de fosses septiques sans sciure de bois (traitement 1, 5 et 9), a augmenté de façon graduelle les rendements en matière sèche de la fétuque rouge et de la fléole des prés. L'addition de quantités croissantes de sciure de bois (traitements 1, 2, 3 et 4) a aussi contribué à augmenter les rendements en matière sèche des deux espèces. D'autre part, l'effet de l'addition de sciure de bois aux boues de fosses septiques sur le rendement a également été mis en évidence. D'après les résultats obtenus, on peut noter que les apports de BFS seuls, SB seuls ou BFS + SB ont permis l'obtention d'une meilleure production que le traitement sans addition de matériaux organiques (témoin). Les traitements 12 et 11 semblent être ceux qui ont le plus favorisé la production de matière sèche chez la fétuque rouge (maximum atteint 13,10 g/pot) et la fléole des prés (maximum atteint 16,00 g/pot) respectivement. On remarque également que la valeur de pH du milieu

Tableau 3. Rendements et teneurs en métaux lours de deux graminés cultivés en serres sur des rejets miniers acides amendés avec des boues de fosses septiques et de sciure de bois

Type de culture	No de traitements[1]	pH des résidus[2]	Rendements en matière sèche (g/pot)	Teneurs (mg/kg) en métaux lourds de la partie aérienne				
				Fe	Zn	Cu	Mn	Al
Fétuque rouge	1	4,10	6,55	87,5	6,5	8,6	155,6	100,4
	2	6,90	6,95	80,2	7,1	8,9	162,8	90,5
	3	6,99	6,67	61,4	7,6	8,8	178,1	80,7
	4	7,18	8,20	44,6	7,5	9,9	204,5	80,6
	5	7,21	8,15	53,1	7,8	8,1	164,7	60,4
	6	6,62	9,30	84,5	10,9	11,2	234,8	105,3
	7	7,05	11,10	48,6	12,4	11,3	186,3	102,3
	8	7,28	10,75	32,4	11,6	11,0	263,5	80,4
	9	6,75	9,40	68,3	17,0	11,0	242,6	86,2
	10	6,88	9,65	65,4	14,7	12,7	259,7	84,1
	11	7,08	12,40	73,4	15,4	10,7	210,8	112,8
	12	7,36	13,10	62,5	18,2	12,4	280,1	105,7
Fléole des prés	1	4,30	6,10	62,5	6,2	8,8	150,3	80,7
	2	6,56	5,92	54,5	8,1	9,2	140,4	120,3
	3	6,83	6,80	57,5	9,4	14,6	170,1	160,6
	4	6,90	8,60	53,5	8,3	13,5	184,2	100,4
	5	6,71	9,55	81,0	9,8	9,7	140,2	130,7
	6	6,85	12,80	98,1	12,4	11,6	127,4	162,6
	7	6,99	15,25	74,3	13,0	12,2	144,3	130,5
	8	7,20	13,75	59,8	13,1	11,7	148,6	110,2
	9	7,08	10,20	70,5	12,1	7,7	122,0	100,4
	10	6,97	12,90	93,2	15,6	11,5	128,0	160,2
	11	7,41	16,00	91,3	16,7	13,8	128,6	160,2
	12	7,48	14,20	86,5	16,8	13,7	182,0	140,5

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[1] La description des traitements est rapportée au tableau 1.

[2] pH des échantillons miniers après la récolte.

Tableau 4. Rendements en matière sèche du lotier et du maïs cultivés en serre et valeurs de pH des échantillons de rejets miniers prélevés à trois profondeurs dans la colonne de lixiviation après la récolte.

Type de culture	Identification des traitements[1]	Rendements en matière sèche (g/colonne)	pH des échantillons de rejets miniers après la récolte		
			Couche 0-10 cm	Couche 10-20 cm	Couche 20-30 cm
Lotier	T1	5,52	6,95	3,40	3,26
	T2	6,91	5,57	3,74	3,36
	T3	6,35	4,74	4,23	3,38
	T4	9,29	5,32	5,00	4,05
Maïs	T1	11,16	6,90	3,95	3,42
	T2	17,13	4,89	4,00	3,67
	T3	15,99	4,20	4,20	3,82
	T4	21,56	5,55	5,14	4,13

[1] La description des traitements T1 à T4 est rapportée au tableau 2.

Tableau 5. Concentrations (mg/L) de métaux lourds dans les effluents provenant de résidus miniers recouverts avec des matériaux organiques et cultivés avec deux cultures.

Type de culture	Identification des traitements[1]	Effluents obtenus après une semaine du semis			Effluents obtenus avant la récolte		
		Fe	Zn	Cu	Fe	Zn	Cu
Lotier	T1	7944	34	460	49,6	1,2	4,2
	T2	6068	36	327	5,3	3,5	8,8
	T3	4435	36	222	2,8	3,0	7,2
	T4	3199	22	142	1,6	2,0	1,7
Maïs	T1	6392	22	282	12,8	1,7	2,9
	T2	5848	30	302	10,6	2,8	4,5
	T3	4252	33	229	5,3	2,2	3,3
	T4	2100	12	165	2,8	1,0	1,2

1 La description des traitements T1 à T4 est rapportée au tableau 2.

de croissance n'ayant pas reçu de matériaux organiques était très faible; 4,10 pour la fétuque rouge et 4,30 pour la fléole des prés. Par contre, les milieux de croissance ayant reçu des doses croissantes de matériaux organiques avaient des valeurs de pH variant entre 6,56 et 7,48.

Les résultats analytiques concernant les teneurs en métaux lourds des plantes sont présentés dans le tableau 3. Les résultats montrent que le taux de prélèvement de métaux lourds par la fétuque rouge et la fléole des prés augmente dans l'ordre suivant: Cu=Zn Fe Al Mn.

Il est à noter que les quantités de Cu ou de Zn prélevées par pot pour les traitements incluant les apports de matériaux organiques étaient, à quelques exceptions près, plus élevées que celles pour les traitements sans matériaux organiques. Ces résultats corroborent ceux de Cescas (1987) et Fuller et Lanspa (1975).

Les teneurs en métaux lourds des espèces cultivées ne semblent pas causer des effets phytotoxiques. Au pH (4,1), auquel a été faite la mise en végétation, on ne s'attend pas à des différences importantes dans l'absorption des métaux lourds dont l'activité est réduite au maximum.

Essais de lixiviation

D'après les résultats du tableau 4, le pH des résidus miniers amendés baisse de façon graduelle avec la profondeur. Il convient de souligner que les valeurs de pH des échantillons de résidus miniers prélevés dans la couche 20-30 cm sont généralement plus élevées que le pH du résidu minier initial (pH=2,41).

Les résultats d'analyse chimique des effluents sont présentés dans le tableau 5. Nous noterons que la quantité de fer relâché dans l'eau de lixiviation baisse considérablement après plusieurs cycles de lixiviation. Le traitement T8 semble être celui qui a le plus empêché la libération de métaux lourds (Fe, Zn et Cu) dans les eaux de lixiviation. De plus, le traitement T4 a favorisé l'obtention de hauts rendements en matière sèche chez le lotier et le maïs-ensilage (tablea 4). De façon générale, le lessivage des métaux lourds n'a pas affecté de façon marquée la croissance des plantes. Le lotier s'est bien développé dans les différents milieux d croissance. Toutefois, le traitement T1 a donné un rendement peu élevé. Ceci peut être attribuable au fait que les amendements organiques n'ont pas été intimement mélangés ave les rejets miniers.

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DESIGN CONSIDERATIONS FOR THE PASSIVE TREATMENT OF ACID MINE DRAINAGE[1]

by

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Abstract. An experimental constructed wetland in the Idaho Springs-Central City mining district provides considerations and recommendations for the design of wetland systems in harsh mountain environments. The application of such systems to metal mine drainages in harsh climates is not well known. The wetland at the Big Five Tunnel is designed to passively treat the metal mine drainage found there. Research objectives include: 1) determining if the wetland system will survive in a mountain climate and in high concentrations of heavy metals, 2) determining the best treatment cell layout for the system, 3) determining the best water distribution system, and 4) identifying the best substrate materials and plant species for such systems. The 55.7 m^2 (600 sq ft) structure is divided into three lined cells which are filled with different mixtures of organic substrates and limestone. An influent and effluent distribution system controls the mine drainage flow into and out of the system. Access wells are used to sample interstitial water in each cell. The species of vegetation growing in the wetland include cattails, sedges, and rushes transplanted from locations of similar elevation. Components of a wetland system must be chosen to optimize efficiency of metal removal. Plants, for example, must be able to resist high concentrations of metals and substrates must provide the best conditions for the appropriate bacteria.

Additional Key Words: constructed wetland, low pH, heavy metals pollution.

Introduction

Acid mine drainage is one of the most persistent industrial pollution problems in the United States. Streams and rivers are adversely affected primarily by underground mines that have been abandoned for decades. Methods used for improving the quality of mine drainage include chemical treatments, where toxic constituents are neutralized and made insoluble, and physical storage treatments where anoxic environments are created that inhibit the growth of iron-oxidizing bacteria. These methods are expensive and have many limitations, especially in remote mountain environments where harsh winters and difficult access make conventional methods too costly. Constructed wetlands have been extensively used in the eastern states as a less expensive alternative to treat mine drainage from coal mines. However, the number of wetlands sites that are actually being used in industrial minerals and metals mining situations are very few. Natural wetlands in Colorado have been shown to raise pH and reduce metals concentrations of acid mine drainages (Emerick 1988, Holm pers. comm.), but only a few artificially created wetlands have been constructed to treat drainage

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from non-coal mines at higher elevations in Colorado (Holm 1983). The objective here is to consider the design parameters necessary for such systems and to provide results from the experimental system at the Big Five Tunnel in Idaho Springs, Colorado.

The Idaho Springs-Central City mining district is located in the foothills of the Colorado Front Range. Around the turn of the century, the region produced a significant amount of precious metal ores. The region is now characterized by massive waste rock dumps, mill tailings piles, and abandoned mine shafts and tunnels. Mine drainage from tunnels typically has low pH and high metal concentrations that create adverse impacts on the aquatic resources of the region. As a result, several sites in the district are included on the National Priorities List under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA or Superfund). The physical characteristics of the Big Five Tunnel make this site a good candidate for investigating the feasibility of using a constructed wetland system to treat the mine drainage (Howard et al. 1988, Guertin et al. 1985). The pilot system is built in a closed configuration to determine the fate of metals in the system, to determine if vegetation exposed to elevated metal concentrations in a mountain climate will survive, to study the occurrence and spatial distribution of various species of bacteria in the system, to identify the organic substrates and plant species that are appropriate for such systems, and to determine the effectiveness of the system in reducing metal concentrations. The design of the system is based on discussions with and findings of experienced investigators (Holm pers. comm., Kleinmann 1983 and pers. comm., Hiel and Kerins 1988). Their suggestions were modified to satisfy the objectives mentioned above and to ensure that the wetland would perform in a harsh mountain climate.

Design and Construction of the Big Five Demonstration System

Methods and procedures used in building and operating the Big Five pilot treatment system include the design and construction of the foundation structure and individual treatment cells, as well as the design of the sampling and preparation of substrate materials for chemical and bacterial tests. Also included are the sampling and analysis procedures for waters from the output drains and wells in each of the treatment cells and from the mine drainage itself.

The completed design of the pilot treatment system is a reinforced concrete structure with dimensions of 0.61 m (2 ft) in depth, 3.05 m (10 ft) in width, and 18.3 m (60 ft) in length. For these initial investigations, the structure is divided into three 6.1 m (20 ft) sections, with provisions to divide the box into six 3.05 m (10 ft) sections at some later time if this were to be desired (Figure 1). The concrete sections, or cells, are separated by walls constructed from 5 x 15 cm (2 x 6 in.) treated wood. Aluminum channels are grouted into void tubes in the concrete walls to allow the addition of lumber to form sidewalls and endwalls of adjustable height. For this initial study, the walls are built up to a height sufficient to allow the total depth of the cells to be 1.22 m (4 ft).

Each cell is fitted with two drains, one active and one reserve. The reserve drains are installed so that the number of cells could be changed from three to six if desired. The drains are made of 15 cm (6 in.) i.d. polyvinyl chloride (PVC) pipe, and the active drains consist of standpipes initially set at a depth of about 1 m (3 ft). The drains deliver the overflow water to the preexisting drainage pond.

A 0.76 mm (30 mil) Hypalon^{R} liner is used to line the cells so that they are separated from one another and to prevent chemical reactions between the treated wood, concrete or aluminum channels and the organic substrates and mine drainage.

Rock baskets were constructed at the upstream end of each of the cells to allow the mine drainage to contact as much of the upstream cross-section of the organic substrate as possible. These baskets, approximately 30-45 cm (12-18 in.) thick, were built using expanded plastic fence and extended to the full depth and width of each of the cells. The baskets were filled with washed 10-15 cm (4-6 in.) river rock. Plastic curtains were suspended from supports just above the substrates on the downstream side of the rock baskets. These curtains extend down to 1/2 to 2/3 of the total depth to force the flow downward into the cells.

Six access wells were installed in each cell to allow sampling of interstitial water. These sample wells were made from 15 cm (6 in.) i.d. PVC and completed to allow water to enter from the lowest, middle, and the upper 30 cm (1 ft) of the organic substrates. Holes in the sample tubes were covered with nylon screen to prevent clogging with the substrate material. Two wells of each completed

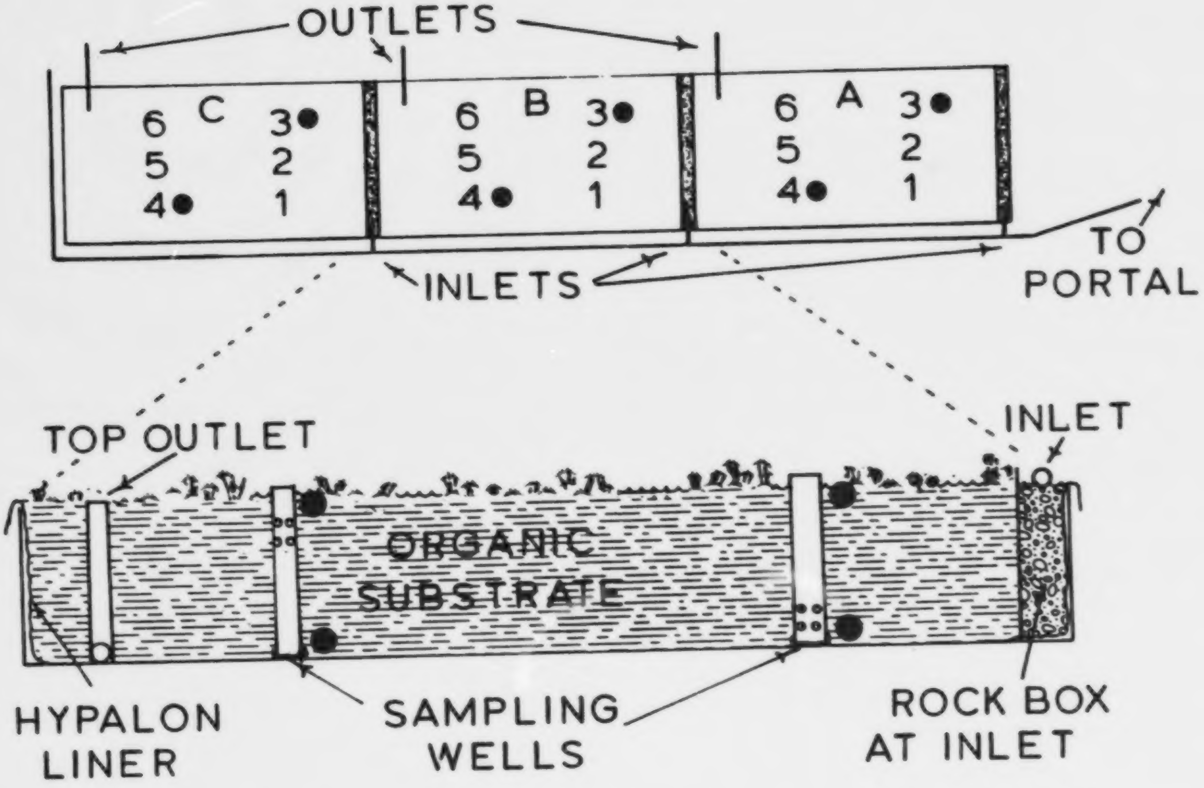

Figure 1. Big Five Wetland Plan View and Cross Section.

depth were placed in each of the 3 cells, for a total of 18 sample wells.

A small concrete dam was constructed just inside the tunnel portal to provide enough head to distribute water to the system. Water is piped from the portal to each of the cells through PVC lines, reduced in size through the system, and fitted with valves to control the total flow and the flow to each individual cell. Due to the harsh winter climate of the location, all plumbing must be insulated by being buried or by using a fiberglass wrap. Water is distributed across the entire width of each cell by allowing it to flow into the rock baskets. Excess water is allowed to drain into the preexisting drainage pond.

After the sample wells were placed and the rock baskets completed, the cells were filled with organic substrates to a depth of about 1 m (3 ft). The first cell was filled with fresh, unused mushroom compost, which consists of approximately 50 percent animal manure and 50 percent barley mash wastes from a local brewery. The second cell received a mixture of equal parts of peat, aged steer manure, and decomposed wood shavings and sawdust. The third cell was filled to a depth of 10-15 cm (4-6 in.) with 5-8 cm (2-3 in.) limestone rock before the cell was filled the rest of the way with the same organic mixture as the second cell. Cattail, sedge, and rush species were transplanted from similar locations to each of the cells. Initially, the organic substrates were saturated with municipal water to reduce stress on the transplanted vegetation. The mine drainage was diverted into the Big Five system on October 25, 1987.

Recommendations for Wetland Treatment Systems Based on the Results of the Big Five System

Research efforts during the past few years have contributed a great deal of knowledge to the design of constructed wetlands for treatment of acid mine drainage. The following suggestions incorporate recent research results with the initial results from the Big Five treatment system. The diversity in individual sites precludes the development of design guidelines that could be applied to all possible situations. Therefore, these recommendations are intentionally restricted to the treatment of discharge from abandoned mines and tunnels in the severe and diverse climates of the Rocky Mountain region.

Preliminary Design Considerations

Preliminary design considerations are based on federal, state and local regulatory requirements. The chemistry of the mine drainage and the hydrology of the site are the two most important factors determining the objectives and decisions to treat wastewater effluent streams (Brodie et al. 1988a and b). Knowledge of the water chemistry and site hydrology are necessary for comparing contaminant concentrations to regulatory standards, and thereby determining the level of treatment required. The availability and costs of plants and substrates, as well as the treatment efficiency of available substrates, must also be determined. These factors, combined with the comparison of long-term economic costs for both constructed wetlands and conventional treatment systems, generally influence the decision on whether or not constructed wetland treatment systems are appropriate in treating acid mine drainage.

Recommendations. (1) A review of all regulations that may apply to the construction of wetland treatment systems and the discharge of effluent from these systems must be done to establish the objectives for the discharge treatment. (2) A good knowledge of the surface and groundwater hydrology is the key to success. Preliminary hydrologic investigations should consist of a complete water budget to include all inflows and outflows of surface water, the precipitation regime, losses from evaporation and transpiration, and subsurface gains or losses. If possible, the first examples should be built to treat point sources, such as the Big Five drainage adit, to ensure a simple hydrologic regime. (3) In the West, there are no examples of wetlands to control nonpoint sources such as seepages from tailings piles or tailings ponds. Also, there are no examples of wetlands used for regional cleanup. Treat either of these situations as highly experimental.

Basic Structure of System

The basic structural components of the Big Five system appear to be functioning as designed. The concrete structure and the separating walls held by the aluminum channels are performing well. The 30 mil Hypalon^R liner used to line the cells remains intact and no leakage from the system has been observed. Recently, the liner withstood a severe hailstorm that shredded 10 mil polyethylene.

Recommendations. (1) All components of the system must be sealed or lined to prevent metals from reaching the underlying groundwater. Plastic liners (e.g. Hypalon^R) and bentonite seals have been used (Howard et al. 1988, Hiel and Kerins 1988).

Mine Drainage Distribution System

The dam and plumbing constructed inside the Big Five adit continues to function adequately in diverting the desired portion of flow to the cells, although the area behind the dam is slowly filling with metal hydroxide sediment. The PVC lines that distribute the mine drainage to the individual cells are insulated adequately, since no freezing of the inflow water has been observed through two winter seasons. The standpipe drains continue to work well in all three cells and clogging has not been observed.

Metal hydroxide precipitates, however, occasionally clog the mine drainage inflow lines. Even though taken from the surface of the impoundment inside the portal, the incoming flow still retains enough metal hydroxide sediments to clog the lines. The lines have to be periodically flushed to remove the sediments in order to maintain the desired flow rates to each of the cells. The reason for the clogging is a trap created by the requirement for installing a vertical section of pipeline to lift the flow to the top of the cells. The problem could be alleviated by avoiding sharp turns and vertical sections in the incoming lines. The clogging of the lines turned out to be serendipitous, however, in that much larger increases in pH values are found when the flow is reduced. This observation led to further studies to quantify the metal removal efficiencies and increases in pH values under different flow rates and retention times.

The rock baskets fill with metal hydroxides after a few months of operation and possibly reduce the opportunity for the mine drainage to contact the entire cross-section of the substrate. The layer of limestone rock in Cell C appears to be somewhat more effective in distributing the flow through the lower part of the substrate. This may not continue, however, as the interstices in the limestone layer become clogged with sediment.

Some of the nylon screens covering the openings in the sample wells become clogged with organic matter, resulting in very slow recharge once the wells are pumped down. These wells are pumped first during sampling to allow time for recharge.

The method of delivering wastewater to the treatment cells depends on the overall system configuration, objectives, and costs. In general, a simple and inexpensive system is preferred over complex plumbing and pumping arrangements.

Recommendations. (1) Where plumbing is necessary, installation of sharp bends or traps in the mine drainage distribution system should be avoided to prevent the accumulation of hydroxide sediments that may clog the lines. It is also advisable to include the capability for cleaning out the lines periodically, should they become clogged. (2) In harsh climates, all lines must be insulated to prevent freezing. (3) The distribution system should be designed so that the flow can be easily adjusted to optimize the treatment efficiency. (4) The water distribution system should be constructed in a versatile manner to allow a module to be bypassed if a problem should develop. (5) If the system is one meter in depth, it becomes important to consider how the water is to penetrate, flow through, and be collected from the complete cross-sectional area of the substrate. (6) Soil conductivity is important if water is to flow at depth. The substrate should be tested before using it to ensure that it will conduct water sufficiently. (7) A rock box at the inlet works well, although the accumulation of hydroxide sediments appears to clog the boxes and they may eventually have to be cleaned. A collection and outlet system that will allow water to uniformly flow through the entire cross section still needs to be designed. Initial tracer tests should be performed to determine the flow patterns through the system. (8) One or more sample wells should be included in each cell if removal mechanisms are to be studied.

Water Quality of the Big Five Mine Drainage and Wetland Outputs

The analytical results of metal concentrations in the cell output waters and mine drainage show promising results for the Big Five treatment system (Table 1). The most abundant metals of concern in the Big Five Tunnel mine drainage are Fe, Mn, Zn, and Cu. These concentrations for the mine drainage remain relatively consistent throughout the year and are the basis for the initial wetland design objectives. Metal concentration reductions range from basically none for Mn to essentially complete removal for Cu. Reductions in concentrations for Fe of up to 60 percent and for zinc of up to 100 percent have been found. Cell A with the mushroom compost has the highest metal removal efficiency and effluent pH.

Recommendations. (1) The chemistry of the mine drainage should be one of the most important factors in determining the objectives and decisions of treating such wastewater effluent streams. Thus, the first step is to build up a data base concerning the mine drainage chemistry.

Substrates

After about 20 months of operation, the mushroom compost in Cell A shows a much better capability to remove metals and raise the pH than the substrates in the other two cells given similar flow rates. The substrate in Cells B and C consists of peat, aged manure, and a wood waste mixture. The bottom of Cell C is also lined with limestone gravel. This difference in the effectiveness of the two types of substrates has been tentatively attributed to the presence of more microbiological activity (Wildeman and Laudon 1988). The substrate in Cells B and C may have experienced a greater degree of decomposition and/or contains fewer nutrients, suppressing the necessary biological activity.

Some investigations have shown that once the microbial-substrate-plant system becomes established, the type of substrate is relatively unimportant (Stillings et al. 1988). This may not be the case for treatment of discharge from metal mines in harsh environments.

Recommendations. (1) Analysis of the substrate prior to its use is imperative. Substrate hydraulic conductivity, pH, buffering capacity, plant nutrient levels, and microbiological activity are tests that should be made. Although some controversy exists, a substrate with near-neutral pH values should be considered so that the activity of sulfate-reducing bacteria will not be suppressed by acidic conditions. (2) Incorporation of gravel beneath the organic substrate material may be advisable to improve permeability and enhance the contact area of the substrate. If substrates have low hydraulic conductivity, some material should be incorporated to increase the permeability. (3) Limestone placed in the treatment system before the metal hydroxides are removed may be quickly coated and therefore

Table 1. Concentrations (mg/L) of metals and sulfate, percent reduction of metals, and pH in the Big Five mine drainage and cell output waters. Cell output flow rates are given in gallons/minute. The area of each cell is 18.6 m^2 (200 ft^2).

	Mn	% red.	Fe	% red.	Zn	% red.	Cu	% red.	$SO_4{}^{2-}$	pH	flow rate
December 11, 1987											
Mine Drainage	34		32		10.6		1.02		1750	2.8	
Output A	27	21	18	45	7.8	27	0.44	57	1560	4.6	1.0
Output B	33	1	24	26	9.8	8	0.89	12	1430	3.1	1.0
Output C	34	0	22	32	9.6	9	0.91	10	1520	3.3	1.0
February 13, 1988											
Mine Drainage	28		28		8.2		0.89		1750	3.3	
Output A	27	4	18	36	5.9	28	0.14	84	1690	4.7	1.0
Output B	31	0	28	0	7.6	7	0.92	0	1780	3.4	1.0
Output C	29	0	28	0	7.9	4	0.92	0	1700	3.4	1.0
May 31, 1988											
Mine Drainage	25		44		8.1		0.75		1500	3.0	
Output A	25	0	27	39	5.4	33	0.03	96	1330	4.3	1.0
Output B	25	0	17	61	7.4	9	0.64	15	1570	3.0	1.0
Output C	25	0	21	52	7.7	5	0.68	9	1220	3.0	1.0
August 19, 1988											
Mine Drainage	26		37		8.1		0.91		1460	2.9	
Output A	25	4	20	46	<0.1	100	0.17	81	650	5.5	0.51
Output B	26	0	15	59	6.1	24	0.55	40	<980	3.2	0.24
Output C	25	4	11	70	5.8	28	0.38	58	1920	3.5	0.34
December 18, 1988											
Mine Drainage	29		38		9.2		0.80		1710	3.0	
Output A	28	3	31	18	8.6	7	0.62	23	1710	3.4	1.21
Output B	28	3	30	21	7.8	15	0.74	8	1700	3.2	1.15
Output C	28	3	29	24	7.7	16	0.69	14	1710	3.3	1.25
February 21, 1989											
Mine Drainage	27		32		9.3		0.56		1860	3.0	
Output A	22	19	12	63	4.5	52	<0.01	100	1690	5.1	0.28
Output B	27	0	28	13	6.1	34	0.82	0	1880	3.4	0.31
Output C	25	7	31	3	7.2	23	0.26	53	2060	3.5	0.32

ineffective in neutralizing the acidity. If limestone channels are necessary to increase the pH to desired values, they should be placed downstream from the treatment system to be effective or in the anaerobic zone where iron exists as Fe^{2+} and will not precipitate at the equilibrium pH of a $CaCO_3$-H_2O system. (4) In harsh climates, depth of the substrate is important if the system is to operate year-round. At least one meter of substrate is needed to maintain an unfrozen anaerobic zone. At 3-4°C, sulfate-reducing bacteria will still function (Batal et al. 1988).

Vegetation

The vegetation transplanted in the fall of 1987 has recovered well in Cells B and C. The plants in Cell A do not appear to be quite as vigorous, possibly due to the differences in the substrate and microbiological processes believed to be occurring in this cell. The speculation is that the level of ammonia was initially too high in the fresh mushroom compost. The health of the plants in Cell A appears to be improving as the decomposition processes continue. Metal uptake by the plants is measurable (around 1%) but remains insignificant when compared to metal removal through the activity of bacteria and algae present in the organic substrate.

Some channelization of surface water is caused by the hasty placement of the transplanted vegetation with respect to maintaining appropriate water levels in the system. Channelization may reduce contact between the acid mine drainage and the organic substrates and thereby reduce the efficiency of the system. Careful placement of the different species of vegetation may be more effective in reducing the channelization. However, in the beginning of the second growth season, the cattails are found dominating the wetland and preventing channelization.

Thus, the presence of vegetation appears to be more important for stabilization of the substrate, reduction of channelization in the surface flow, and continual additions to the biomass of the system than for metal uptake. Metal uptake by plants is also found to be insignificant in comparison to metal removal through other processes by Sencindiver and Bhumbia (1988). The choice of the species of vegetation, therefore, is not of primary importance, as long as they are able to tolerate the conditions of the acid mine drainage and local climate. Since the concept is to emulate a natural ecosystem, complexity may be favored rather than simpler systems (Hammer and Bastian 1988).

Recommendations. (1) Local species of vegetation that are tolerant of the environment and climate are the best choices. (2) Any vegetation available on site should be saved and used. Plant species from other local mine drainage situations are good candidates. (3) Any method that can save labor in transplanting vegetation and still make a uniform planting should be used. Since providing biomass is a primary objective, neat plantings are not necessary, although placement should be done so that channelization is minimized.

Area Requirements

Once the decision to construct a wetland system is made, an estimate of the area required to treat the mine drainage must follow. This estimate must be based on data obtained through the preliminary survey including water chemistry, site hydrology, desired discharge quality and, equally important, the expected efficiency of the planned system. One of the most critical factors that determines the efficiency of the system is the retention or contact time in each cell. The interrelationship of all these factors is imperative for the design of successful systems, but presently is not well known. The lack of success of some systems can be attributed to insufficient treatment area and inadequate knowledge of site hydrology (Hiel and Kerins 1988, Brodie et al. 1988c).

Brodie et al. (1988a) developed preliminary general guidelines for treatment area requirements for desired effluent discharge concentrations of Fe = 3 mg/l or less and Mn = 2 mg/l or less as follows:

$$\text{Fe: } 2\ m^2/mg < pH\ 5.5 > 0.75\ m^2/mg \qquad (1)$$

$$\text{Mn: } 7\ m^2/mg < pH\ 5.5 > 2\ m^2/mg \qquad (2)$$

These values suggest a treatment area for Fe of 2 m^2/mg/min, and for Mn, 7 m^2/mg/min, when the pH is less than 5.5 units.

Applying these values to the mine drainage of the Big Five demonstration site, with a discharge to each cell of 3.8 l/min (1 gpm) and concentrations of Fe and Mn of 50 and 32 mg/l, respectively, the area requirement can be estimated. For iron, the rate factor is 2 m^2/mg/min, therefore the area required is:

$$(2\ m^2/mg/min)(3.8\ l/min)(50\ mg/l) = 380\ m^2 \qquad (3)$$

For manganese, the rate factor is 7 m^2/mg/min, and the area required is:

$$(7\ m^2/mg/min)(3.8\ l/min)(32\ mg/l) = 850\ m^2 \qquad (4)$$

Under these conditions, Mn becomes the limiting factor for the area required. In order to reduce Mn concentrations to 2 mg/l, the treatment area requirement would be 850 m^2 (9160 ft^2) or about 0.25 acre. Research conducted at the Big Five Tunnel demonstration site, however, shows that the pH of the effluent is very responsive to changes in flow. Good results for heavy metal removal are obtained using a substrate of fresh mushroom compost with flow rates equivalent to 400 sq ft/gpm.

Recommendations. (1) All area requirements are crude rules of thumb. Research and demonstration sites have to be studied over a period of years to establish better guidelines. (2) Area requirements are substrate dependent. In places where flat land is at a premium, preliminary study of possible substrates is essential. (3) A wetland should be used as the first or last stage of a several-stage design that would include some sort of maintained operation or standby chemical treatment system. In this context, the wetland serves to make the treatment plant a small part of the operation. (4) Never commit to cleanup with an area of less than 1000 sq ft/gpm.

Configuration

In field scale constructed wetland systems, great diversity exists in the number and arrangement of cells. The basic intent is to maximize contact time in the wetland while still treating the entire discharge. As shown in Figures 2A and 2B, a typical configuration may be a parallel or series arrangement of cells. The Big Five System uses a parallel arrangement in order to assess the performance of three different substrate mixtures. Some systems have been constructed with a limestone layer as in Cell C at the Big Five system and other systems have additional aeration structures to exsolve CO_2. Some designs also include limestone channels to neutralize acidity (Hiel and Kerins 1988, Hedin et al. 1988).

Recommendations. (1) The best configuration for any system and the only configuration for a large system is a modular design incorporating parallel and series components (Figure 2C). The parallel portions allow for overflow, backup, and easier uniform distribution of influent. The series portions allow for different ecosystems to treat different aspects of the problem. In this type of system, failure of one cell would not destroy the whole project.

Summary

Preliminary results indicate that wetland systems can survive in harsh mountain climates and in high concentrations of heavy metals. Such systems can be used as primary treatment of acidic drainages with high metal concentrations and must optimize an entire ecosystem. Optimization of many parameters is necessary to increase the efficiency of metal removal in wetland treatment systems. Such parameters include layout of treatment cells, substrate composition, influent and effluent distribution systems, access wells for sampling, and types of plants. Plants must be able to resist high concentrations of metals, and substrates must provide the best conditions for the appropriate bacteria to thrive. Many aspects of the design of wetland systems must be site specific and depend on such things as area available for the system, climate at the site, wastewater metal concentration and pH, site hydrology, and degree of treatment needed.

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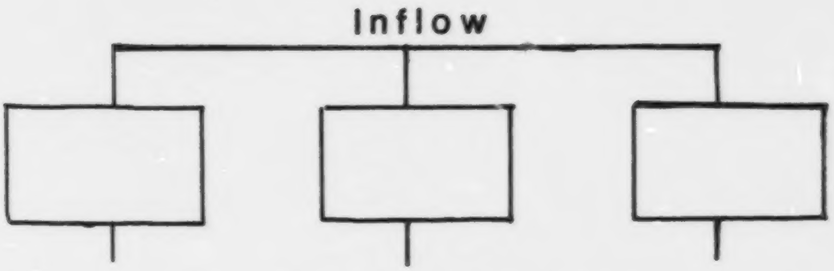
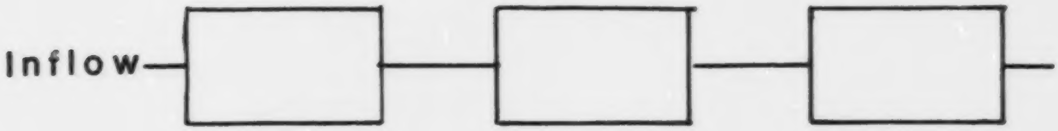
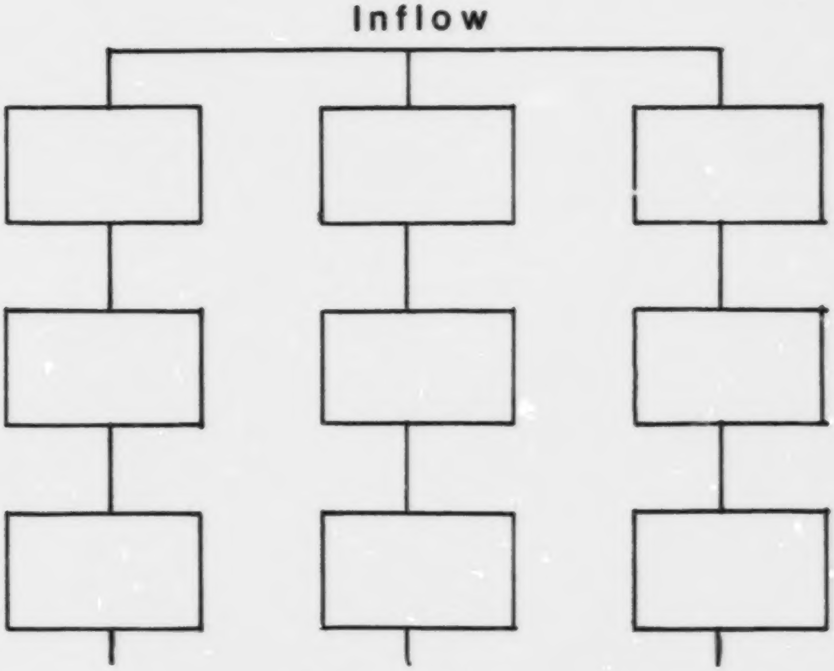


A. Parallel Modules



B. Series Cells



C. Combination Arrangement

Figure 2. Wetland System Configurations.

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ECOLOGICAL ENGINEERING MEASURES DEVELOPED FOR ACID GENERATING WASTE

Biological Polishing for Acidified Lakes

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Abstract.A copper/zinc concentrator located in the Red Lake area, northern Ontario, was shut down in 1981. In an area of 25 hectares, 760,000 tonnes of tailings are contained within low dams. The tailings contain about 41% pyrite and 4.1% pyrrhotite. The 75 hectare mine site, including the town site and mill, is surrounded by recreational fishing lakes of the English River drainage basin. Decommisioning procedures include those steps which will assure acceptable surface water quality in the long term. As Ecological Engineering appeared suitable in providing such a solution to acid generating wastes on this site, efforts were directed towards development of measures using this approach. An acidic ground water plume generated by the tailings was intercepted with ditching and a polishing pond was created. The biological polishing capacity of endemic biological polishing agents, identified as algal complexes dominated by *Achnanthes* and *Mougeotia* spps. in acidic (pH 3.5) water, are evaluated after 2 years' growing seasons. An acid-tolerant aquatic moss was introduced in the polishing system. The moss carpets cover the sediment surface, providing a permanent sink for metals removed by the polishing agents. This paper provides a description of this Ecologically Engineered system and its expected long term performance.

ADDITIONAL KEY WORDS: Acid mine drainage; biological waste water treatment; close-out; Ontario, Canada

Introduction

The Ecological Engineering methods which are being developed are based on the results of ecological studies carried out on the natural recovery process which takes place on tailings sites. The principles of this technology have been presented in detail by Kalin and van Everdingen (1988).

It is intended that these Ecological Engineering systems will be self-sustaining in the long term, as well as being maintenance- free. The measures are being tested on a tailings site from a copper/zinc concentrator in Northern Ontario, Canada. A feasibility study was initiated in 1986 and the close-out measures applicable to the site conditions are described by Kalin (1989).

This paper reports on the Ecological Engineering measures which have been implemented between 1986 and 1988 for a drainage basins containing 760,000 tonnes of acid-generating tailings containing 43% metal sulphides.

Site description

The waste-management area can be divided into three units - the tailings area with Decant Pond, the Boomerang Lake basin and the Mud Lake basin. Map 1 provides an overview of the site and identifies all major locations where remedial measures have taken place. The South Bay site is surrounded by Confederation Lake which is part of the English River drainage basin. The tailings, located close to Boomerang Lake, provide the main source of acid generation. Boomerang Lake has acidified (pH 3.5) over the life of the mill and displays increasing concentrations of zinc.

Contaminated water arises from the tailings area at a total of about 30,000 m^3 per annum. This water leaves the basin in four directions, two of which reach Confederation Lake directly and two indirectly through Mud Lake and Boomerang Lake. The annual flow volume estimates and the flow directions were determined based a hydrological investigation. On an annual basis, a total water volume of about 335,000 m^3 can be expected to move through the Boomerang Lake drainage basin.

Tailings and contaminant production

The elemental concentrations in the water collected from within the tailings exhibited large ranges. Therefore, to estimate the acid mine drainage production which takes place annually, a range of the concentrations of oxidation products was used (minimum and maximum values) along with an average. Table 1 gives the results of the calculations of the oxidation and precipitation products which can be expected to form from the tailings pile of 760,000 tonnes.

The tailings have an average 43% Fe + Cu + Pb + Zn + S content. The tailings exhibit a relatively high ratio of metals to sulphur (0.6 to

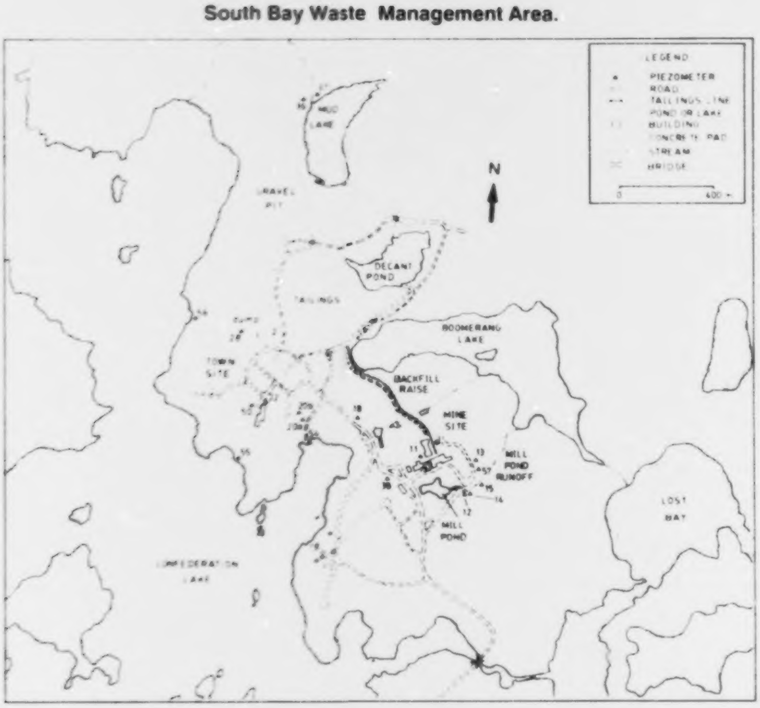

South Bay Waste Management Area.
LEGEND
PIEZOMETER
ROAD
TAILINGS LINE
POND OR LAKE
BUILDING
CONCRETE PAD
STREAM
BRIDGE
0
400 m
N
MUD LAKE
GRAVEL PIT
DECANT POND
TAILINGS
BOOMERANG LAKE
TOWN SITE
BACKFILL RAISE
MINE SITE
MILL POND RUNOFF
MILL POND
LOST BAY
CONFEDERATION LAKE

Figure 1: Overview of South Bay Waste Management Area.

0.75), which no doubt reflects the presence of pyrrhotite, although some iron may be present in silicate minerals in the tailings.

The acid-generation potential of the tailings is considered with respect to pyrite and pyrrhotite content. The rate at which pyrite is depleted from the tailings deposit, based on the minimum sulphur concentrations in the water, is estimated to take approximately 35,700 years. Based on the highest concentrations in the water, this process is estimated to take 1,100 years. The acidity which can be produced ranges from 530 to 16 tonnes of $CaCO_3$ equivalent per year. These tonnages can be produced and are potentially discharged with a delay ranging from 0.45 years to 3.2 years. Precipitation of iron hydroxide is expected to occur with an estimated annual volume of sludge produced ranging from 80 to 2,576 m^3.

From these estimates of annual contaminant generation, one important point emerges and that is the need for a self-sustaining treatment system, as

Table 1: Calculating the potential acid production

PARAMETER	MINIMUM	AVERAGE	MAXIMUM
Tailings. tonnes	760.000	760.000	760.000
Average density of material. t/m^3	3.65	3.65	3.65
Average bulk porosity. fraction (est.)	0.30	0.30	0.30
Volume. m^3	297.353	297.353	297.353
Surface Area. m^2	200.000	200.000	200.000
Average thickness. m	1.5	1.5	1.5
Initial FeS2 + FeS. mass fraction	0.45	0.45	0.45
Initial pyrite + pyrrhotite. tonnes	342.000	342.000	342.000
Initial pyrite + pyrrhotite. moles	2.94E+09	2.94E+09	2.94E+09
Initial neutr. cap., mass fraction (CaCO3)	0	0	0
Initial neutralizing capacity. tonnes CaCO3	0	0	0
Net mean annual infiltration. m/yr	0.15	0.15	0.15
Average thickness saturated. m	0.94	0.94	0.94
S concentration. mg/L	176	1.669	5.668
SO4 concentration. millimoles/L	5.5	52.1	176.8
Acidity. mg/L	133	9.191	30.120
Fe concentration. mg/L	31	2.328	9.857
Initial SO4 flux. mol/m^2.yr	0.82	7.81	26.52
Pyrite depletion rate. mol/yr	82.346	780.880	2.651.903
Minimum depletion time. yr	35.742	3.769	1.110
Acid production rate. tonnes/yr (CaCO3)	16	156	531
Neutralizing capacity exhaustion period. yr	0	0	0
Acid storage capacity. tonnes (CaCO3)	7.5	516	1.692
Potential discharge delay. yr	0.45	3.30	3.19
PRECIPITATES:			
Maximum Fe(OH)3 quantity. tonnes	314.537	314.537	314.537
Fe(OH)3 production. t/yr (if all from FeS2)	9	83	283
Fe(OH)3 production. t/yr (if all from FeS)	18	167	567
Potential sludge volume at 10% solids. m^3	2.859.424	2.859.424	2.859.424
Annual sludge volume. m^3/yr	80	759	2.576

CONSTANTS USED:	
mol. weight SO4	96.06
mol. weight FeS2	119.9
mol. weight FeS	87.90
mol. weight CaCO3	100.0
mol. weight Fe(OH)3	106.8
mol. weight CaSO4.2H20	172.1
Conversion factor. g/tonne	1E+06
Conversion factor. tonne/g	1E-06
Stoichiometric ratio. 2 SO4 -> 1 FeS2	0.5
Stoichiometric ratio. 1 FeS2 -> 2CaCO3	2

even with maximum oxidation rates, treatment of the contaminants will be required for at least 1,100 years.

Ecological Engineering measures

It has to be recognized that water must be brought to the surface before its quality can be addressed with Ecological Engineering measures. The contaminant loadings to Boomerang Lake are the sum of contributions from allochthonous sources (run-off from the mine site and spill areas, and ground water discharge from the tailings) and autochthonous sources (metal flux from the sediments). Processes relevant to the removal of these contaminant sources are, sedimentation of particulate matter, contaminant flux from the sediment and dissolution of contaminants.

The suspended solids loading received by Boomerang Lake is small, due to the fact that no direct fresh water input exists to the lake. The processes which will drive zinc removal from the water column are adsorption on and co-precipitation with manganese oxides as well as with amorphous iron oxides, and adsorption on organic matter. The adsorption affinities of zinc, however, are affected by pH, Eh, mineralogy and organic acids. The natural removal processes for zinc vary, therefore, depending on local conditions. In order to enhance these natural removal processes, conditions have to be created which support those processes, for example the production of organic matter.

Periphytic algal growth on suspended branches in the lake could contribute significantly to zinc removal if submerged surface areas were provided on which extensive growth could occur. Therefore, log booms have been installed, behind which brush has been placed. The biological polishing capacity which has developed on this brush consists mainly of an algal complex dominated by *Achnanthes* and *Mougeotia* spps.

The concentrations of iron, copper, sulphur and zinc contained in this algal material after two growing seasons and those for an undetermined length of time suggest that one of the major processes of removal will be the co-precipitation of metals with iron hydroxides.

Although the increase of iron content from one growing season to the second is notable (20 g/kg increasing to 40 g biomass /kg substrate), the metal concentrations in the algal mat do not increase proportionally. The concentrations of iron and zinc in algal mats collected from those branches where the time of suspension is unknown were one order of magnitude higher (166 g/kg and 6 g/kg,), compared to two years' growth

(40 g/kg and 0.5 g/kg) respectively.

The algal growth on the branches of the brush will be relegated to the bottom sediments after sloughing, a process promoted by wave action. The sediments in the lake will be enriched with the metals adsorbed by the algal complex. Therefore, a reducing environment has to be maintained over the sediments to prevent resolubilization of the metals.

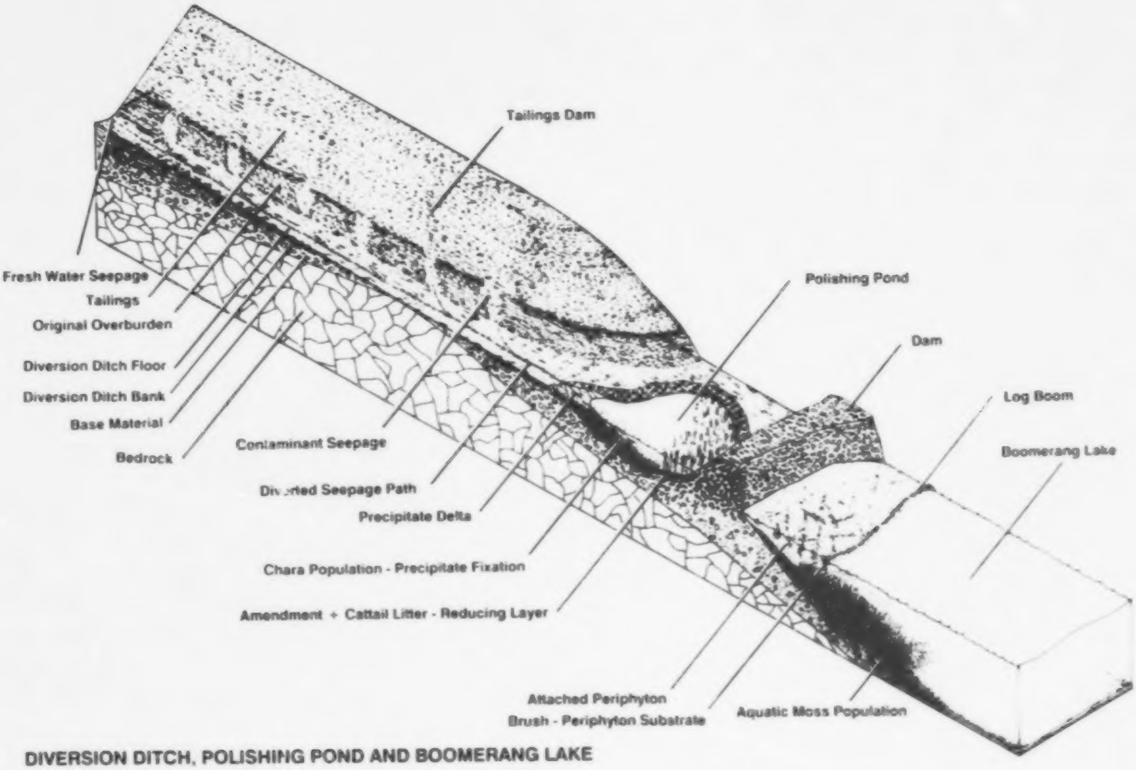
For this purpose, within areas enclosed by log booms, submerged aquatic moss has been introduced, where decaying basal portions serve to consume oxygen above the sediments. From the investigation of a lake (pH 3.5) in Northern Saskatchewan which received tailings, it was found that this species of moss covered the entire lake bottom and provided an effective barrier to oxygen over the sediment (Kalin, 1985). Its ability as a cation-exchange medium was found to be limited in the presence of concentrations of iron greater than 35 mg/l in acidic waters (Buggeln and Kalin, 1986). However, the moss surface functions as an adsorption and precipitation site, as well as providing filtration capacity for particulates.

The components described above, algal biomass and moss-covered sediment, constitute the biological polishing system in Boomerang Lake for the removal of zinc. Thus, it will be important to provide sufficient surface area for algal growth and to develop an extensive cover of submerged aquatic moss. It is expected that, before too much longer, such a system will be established in the shallow part of Boomerang Lake near the outflow, since the most extensive growth of moss and algal material has been noted in this area after the first year of placement of the brush.

In Figure 2, an overall representation of the combination of the measures described previously, together with the precipitation and neutralization systems is made. The polishing system in the acidic lake is complemented by precipitation/neutralization which is expected to occur in a groundwater-interceptor ditch and a polishing pond which have been constructed. Their location was determined by the topography of the tailings and the prevailing groundwater flows.

Although data with respect to the quantification of the expected function of the interceptor ditch are not available at this stage, it is reasonable to expect that precipitation of iron hydroxide will occur as the tailings seepage is exposed to the air. The precipitation process will be further enhanced by the mixing of the seepage water

Figure 2: Conceptual representation of the Ecological Engineering measures for an acidified lake


Tailings Dam
Fresh Water Seepage
Tailings
Original Overburden
Diversion Ditch Floor
Diversion Ditch Bank
Base Material
Bedrock
Contaminant Seepage
Diverted Seepage Path
Precipitate Delta
Chara Population - Precipitate Fixation
Amendment + Cattail Litter - Reducing Layer
Polishing Pond
Dam
Log Boom
Boomerang Lake
Attached Periphyton
Brush - Periphyton Substrate
Aquatic Moss Population
DIVERSION DITCH, POLISHING POND AND BOOMERANG LAKE

with uncontaminated ground water drawn into the ditch from the other side. Some neutralization can also be expected to occur through the addition of this uncontaminated water.

The settling pond at the lower end of the interceptor ditch will facilitate completion of the precipitation step, allowing settling of the precipitate. A neutralizing buffer can be established through the introduction of a *Chara* population. Such a population has colonized a seepage path leaving the tailings in the northern direction. *Chara* populations accumulate calcium and magnesium carbonate on the outside of their cell walls during growth, and in this way serve as a buffer to the expected acidification (Kalin & Smith, 1986; Smith & Kalin, 1988).

Assessment of the implemented measures

At this early stage of the implementation, i.e. at a time when the system is only beginning to function, it is not possible to quantify its effectiveness. Some discussion can be had, however, addressing the qualitative effectiveness of the measures implemented to date.

The metal and sulphate removal capacity of the system will depend on the rates at which the processes employed occur. Those are: the growth rates of the biological agents, the rate of sulphate reduction, the rates of adsorption, co-precipitation and precipitation of metals, and the rate at which the contaminants are produced in the three drainage basins. To enable a determination of some of these rates, data have been collected.

Quantification of biomass of the polishing agents has been carried out for the algal material growing on the brush cuttings from Boomerang Lake. The results are presented in Figure 3, expressed as algal biomass weight per kg of growth substrate versus the number of days the material was suspended.

Absolute growth rates cannot be obtained from the accumulation of biomass, as wave action continuously strips biomass which settles to the sediments. The assumption is made that the amount of biomass relegated to the sediment is, on average, the same throughout the year. However, the quantities of biomass determined per kg of substrate suspended (both air dried in an oven at 60°C) indicate that an incremental increase in biomass is noted after about 180 days of suspension from 200 g/kg to 500 g/kg (Figure 3).

An estimate was made with respect to the total growth substrate which might be provided by a spruce tree of dimensions similar to those used as part of the brush suspended in Boomerang Lake. One tree can be expected to produce about 40 kg of growth substrate in addition to the trunk and can therefore be estimated to provide substrate for about 8 kg to 20 kg of algal biomass /unit tree. On the average this biomass contains 4.2% Fe, 0.02% Cu, 0.003% Pb, and about 0.05% Zn after two years of growth. These concentrations increase with time to 16% Fe, 0.1% Cu, 0.02% Pb, and 0.6% Zn based on concentrations determined in biomass suspended for an undefined period of time. Therefore using a unit tree to evaluate the polishing capacity for the removal of Zn in Boomerang Lake, where the annual loading ranges from 1.4 tonnes to 2.5 tonnes, results in a requirement of 10 to 15,000 trees, or the equivalent quantity of brush.

In Figure 3, the biomass quantities of moss which has been growing for different lengths of time are presented. Again the biomass quantity determined after two growing seasons is significantly higher than that obtained within one growing season. It is likely that this increase is due to the adhered material on the non-growing parts of the moss strands. The rate of growth the first year following introduction of the moss was about 0.4 to 0.8 $g/m^2/day$ and, in the second growing season, about 1.5 $g/m^2/day$, due primarily to the higher biomass weights. Moss bags which were harvested in spring after overwintering displayed no growth during the winter as expected, with a negative growth rate of 0.02 $g/m^2/day$. Through continued apical growth a thick carpet of moss is attained, ensuring a reducing environment in the sediments below.

These estimates of polishing capacity are limited in their reflection of the real polishing capacity, for the following reasons: firstly, it is impossible to quantify the surface area provided by the brush placed behind the log booms, which may well be equivalent to the quantity required to remove the annual loadings of contaminants. Furthermore, these values were obtained during the establishment phase of the system, at a time when functioning at full capacity could not be expected. With progress of the populations, in terms of growth rates and lateral spread, increased polishing rates can be expected.

Thirdly, as the conditions in the lake improve, due to the reduction of contaminant loading which can be expected from the implementation of the measures at other locations on the site and through the

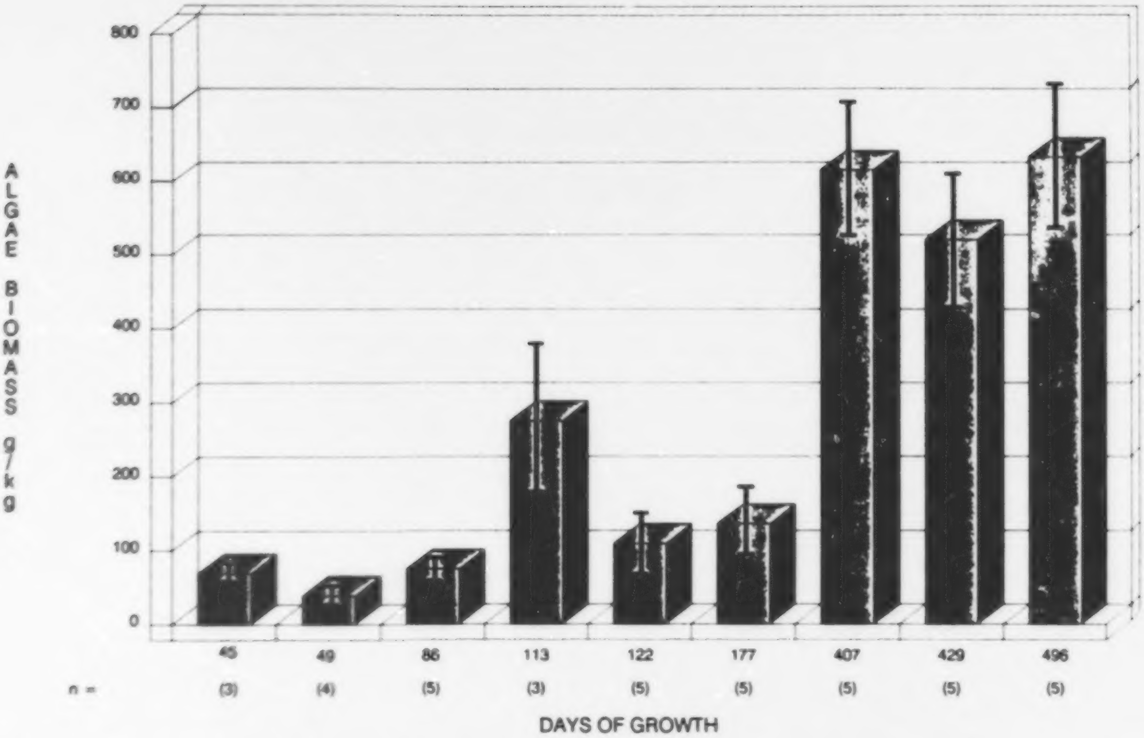


Figure 3: Biomass productivity of algal mats on cut brush

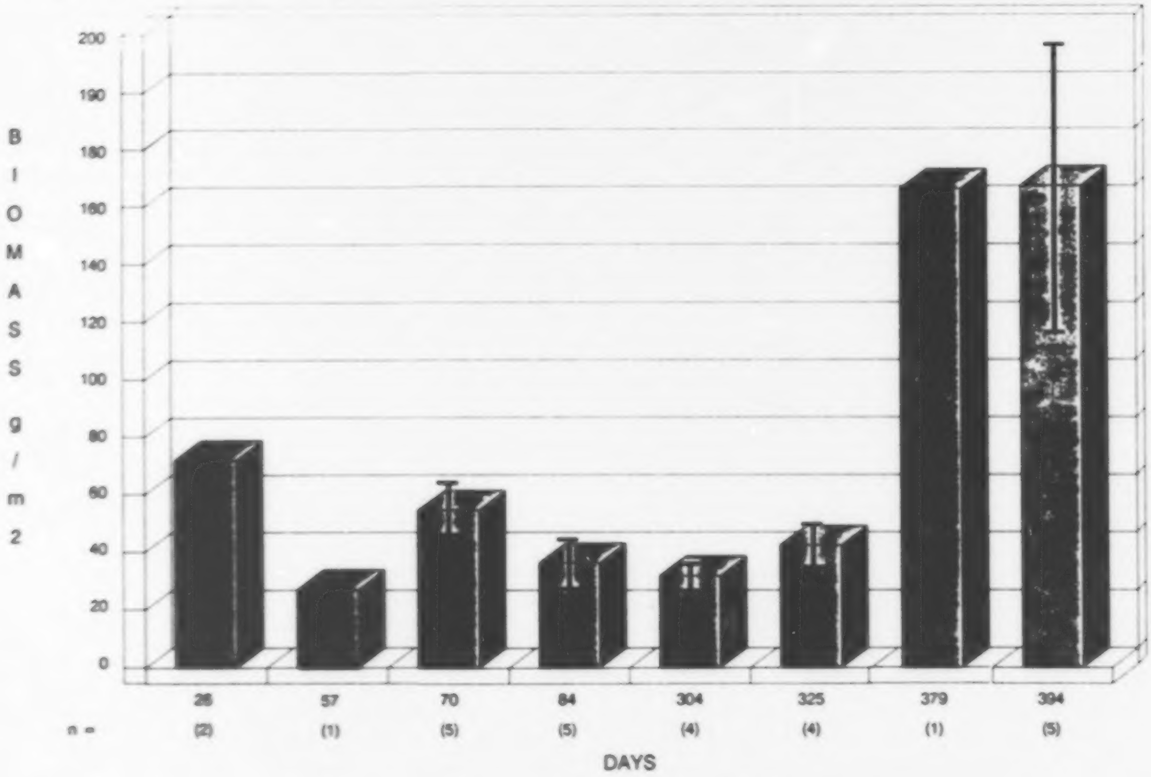


Figure 4: Moss biomass produced during the growing season

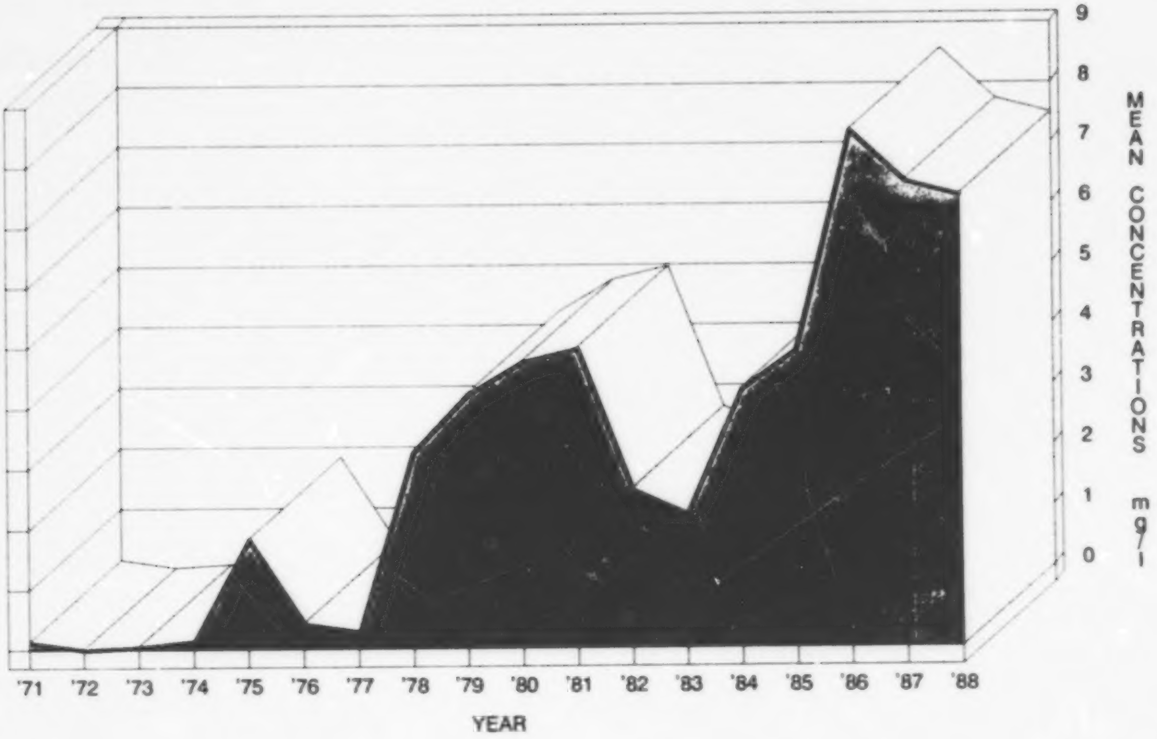


Figure 5: Zinc concentrations in Boomerang Lake from 1971 to 1988

interceptor ditch, colonization by other biota will increase.

The ultimate proof of the effectiveness of the measures implemented can only be obtained directly by a determination of the concentrations of zinc in Boomerang Lake. In Figure 5, the zinc concentrations in the lake since 1971 are given. A steady increase can be noted up to 1981, whereupon a decrease by an average of 2 mg/l was observed in 1982, attributable to liming. The remnants of this liming activity are still noticeable in the lake. Within the same year, the concentration of Zn in the lake continued to increase. The 1986 year marked the beginning of the implementation of the Ecological Engineering measures and a slight decline in the Zn concentrations is evident by 1988.

Given that the time lag with which the ground water from the tailings reaches the lake can range from about 0.45 years to about 3 years, the downward trend noted in zinc concentrations is promising. However, only a continued downward trend in zinc concentrations will confirm the effectiveness of the measures taken.

Conclusion

This is the first implementation of Ecological Engineering measures to achieve a walk-away scenario from an acid-generating tailings area, and many questions remain to be answered. However, without such an on-site demonstration, it would not be possible to determine the actual effectiveness of these measures.

From the results of the first two years of the project, it can be concluded that the measures which were put in place appear to hold promise for a long-term performance.

Acknowledgements

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MICROBIAL SULFATE REDUCTION FOR THE TREATMENT OF ACID MINE DRAINAGE: A LABORATORY STUDY[1]

by

R. W. Hammack and R. S. Hedin[2]

Abstract. A laboratory study was conducted to determine if sulfate-reducing ecosystems can effectively treat acid mine drainage in the presence and absence of calcareous substrates. Four anaerobic mesocosms (20 L) were created in the laboratory by inundating carboys containing spent mushroom compost and allowing native fermentative organisms and sulfate-reducing bacteria to become established. The mushroom compost in two carboys was underlain by calcareous gravel; the other two carboys contained a noncalcareous gravel substrate. Simulated acid mine drainage was passed through each carboy and samples of the inflow and outflow were analyzed to determine pH, acidity, alkalinity, and concentrations of iron, manganese, sulfate, and calcium. At influent pH 4-5, about 90 pct of the iron and 80 pct of the manganese were removed with a single pass through the mesocosms. At influent pH 2.5-3.5, about 80 pct of the iron and 50 pct of the manganese were removed. About 55 pct of the sulfate was removed irrespective of influent pH. All effluents from the mesocosms exhibited a circumneutral pH and had slight net alkalinity. The presence or absence of a calcareous substrate did not significantly affect the pH and alkalinity of the effluents or the quantity of iron and sulfate removed. However, mesocosms with calcareous substrates were more effective in removing manganese. Results of this study indicate that existing anaerobic organisms will remain active in the presence of acid mine drainage and significantly improve water quality.

Additional Keywords: mine water, dissimalatory sulfate reduction

Introduction

Drainage from high-sulfur coal mines in the Appalachian Coal Basin is commonly acidic and contains elevated concentrations of sulfate, iron, aluminum, and manganese. Prior to release into receiving streams, contaminated mine effluents must be neutralized and the concentration of iron and manganese reduced to meet statutory limits. This treatment is usually accomplished with aeration and chemical neutralization at great expense to the mine operator. Recently biological treatment has become popular because it offers long-term, low-maintenance treatment at low-cost.

In 1979, a group of Japanese researchers (Wakao et al. 1979) found that acid mine drainage (AMD) could be successfully treated using dissimilatory sulfate-reducing bacteria. However, their laboratory results were based on nutrient addition to wood dust in an anaerobic reactor and were never applied to the field. In 1988, the Bureau of Mines found that microbial sulfate reduction was occurring in the thick organic substrates in some wetlands constructed to treat AMD (Hedin et al. 1988). In fact, sulfate reduction was found to be an important process contributing to the successful treatment of AMD in these wetlands. When inundated with AMD, spent mushroom compost, a byproduct of mushroom cultivation consisting of composted manures, straw, corncobs, and an occasional horseshoe, was found to support the growth of sulfate-reducing and fermentative bacteria. However, all constructed wetlands found to be actively reducing sulfate had limestone gravel underlying mushroom compost (Hedin et al. 1988). This made it impossible to determine if the circumneutral pH in the wetland substrate only a few centimeters below pH 2.5 surface waters was due to: (1) alkalinity naturally in the compost, (2) alkalinity generated by sulfate reduction, or (3) alkalinity resulting from carbonate dissolution. This paper contains a brief introduction to dissimilatory sulfate-reducing bacteria and results of laboratory AMD treatment using sulfate-reducing bacteria grown on mushroom compost.

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Dissimilatory Sulfate Reduction

Dissimilatory sulfate-reducing bacteria reduce inorganic sulfate or other oxidized sulfur forms to sulfide. This sulfide is not incorporated into the organism but is released as "free" H_2S. Desulfovibrio and Desulfotomaculum are the two best known genera of dissimilatory sulfate-reducing bacteria. Others include Desulfobulbus, Desulfococcus, Desulfosarcina, Desulfobacter, and Desulfonema, although the latter three genera are restricted to marine environments (Postgate 1984). Dissimilatory sulfate-reducing bacteria are strict anaerobes that are severely inhibited by even small amounts of oxygen. They will, however, survive long periods of oxygen exposure and become active when anaerobic conditions are restored.

Dissimilatory sulfate-reducing bacteria are heterotrophs and therefore require an organic carbon source. In the case of Desulfovibrio spp., this carbon source can be supplied by simple organic molecules such as lactate, pyruvate, and malate. These are subsequently oxidized to acetate and CO_2 with the concurrent reduction of sulfate to sulfide (Ehrlich 1981). Like Desulfovibrio spp., Desulfotomaculum spp. prefer to oxidize lactate and pyruvate to acetate and CO_2, although one species, Desulfotomaculum ruminis, can also oxidize formate to CO_2. Several species, including Desulfovibrio baarsii, Desulfococcus multivorans, and Desulfotomaculum acetoxidans are capable of oxidizing acetate (Postgate 1984) to CO_2 with the concurrent reduction of oxidized sulfur species. Because sulfate-reducing bacteria can oxidize simple organic compounds and will only oxidize carbohydrates under rare circumstances (Ehrlich 1981), they generally rely on fermentative bacteria and fungi to break complex organic compounds into simple molecules prior to utilization.

In the natural environment, dissimilatory sulfate-reducing bacteria can be found growing at temperatures between 0 and 70° C. Desulfovibrio spp. grow between 0 and 44° C with optimum growth occurring between 25 and 30° C. Desulfotomaculum spp. prefer higher temperatures (30-70° C) with optimum growth occurring between 35 and 55° C (Ehrlich 1981). Sulfate reduction is thought to cease when the pH drops below 4 (Wakao et al. 1979). This is supported by the observation that mixed cultures of sulfate-reducing bacteria and heterotrophic bacteria can become established in solutions with an initial pH as low as 2.7 (Wakao et al. 1979), but sulfate reduction does not commence until the pH rises above 4.

The overall sulfate reduction process can be represented by the following generalized equation:

$$\text{Fermentative end products} + SO_4^{2-} \text{-->} \text{acetate} + HS^- + HCO_3^- \qquad (1)$$

The end products of biomass fermentation and sulfate are converted by this reaction to acetate, bisulfide or hydrogen sulfide, and bicarbonate. Application of this process to acidic mine effluents may improve water quality in five respects:

1. the process consumes sulfate which, although unregulated at present, is undesirable in high concentrations,

2. sulfide generated either in the form of bisulfide or hydrogen sulfide should react quickly with many metals to form

insoluble precipitates and decrease dissolved metal concentrations,

3. alkalinity generated in the form of bicarbonate and acetate will help neutralize acidity and raise pH,

4. aluminum will precipitate as a hydroxide in response to the pH increase, and

5. manganese may precipitate as a carbonate in the presence of high pCO_2.

In fresh waters, sulfate reduction is commonly limited by the availability of sulfate. However, because high sulfate levels are characteristic of AMD, sulfate reduction in the presence of AMD would not be sulfate limited and would likely occur at a faster rate than in fresh waters.

An organic-rich, anaerobic environment must be engineered and an active population of sulfate-reducing bacteria and fermentative organisms established before the treatment of mine effluents can begin. These engineered environments can take the form of tanks such as the anaerobic digesters used for the treatment of municipal wastewaters or the constructed wetlands with thick organic substrates used for AMD treatment. It is desirable that AMD be introduced with minimal dissolved oxygen because sulfate-reducing bacteria are inactive in the presence of oxygen. Aerated mine waters will require systems of higher capacity or longer flowpaths to allow aerobic organisms time to remove dissolved oxygen.

In order to evaluate sulfate reduction as a possible AMD treatment method, experiments were carried out in the laboratory where reactions could be carefully monitored. Specific objectives of this research were:

1. to determine if fermentative and sulfate-reducing bacteria indigenous to mushroom compost remain active in the presence of AMD,

2. to determine if water quality is improved by passage through a sulfate-reducing ecosystem, and

3. to determine if a calcareous substrate is beneficial to the performance of an AMD treatment system using sulfate reduction.

Experimental

Four mesocosms were constructed from 21.5 X 31 X 34.5 cm plastic carboys (20 L capacity). Each carboy was filled with 4 kg (6 cm) of either calcareous or noncalcareous gravel (minus 5 cm) overlain with 8 kg (25 cm) of spent mushroom compost. Initially, all mesocosms were leached with deoxygenated, deionized water until the effluents contained less than 5 mg/L sulfate and 1 mg/L iron. Twenty 50-L batches of simulated AMD were made by dissolving reagent-grade ferrous sulfate heptahydrate, manganese sulfate monohydrate, and sodium sulfate in 16 megohm deionized water. The pH was adjusted by adding 0.5 M sulfuric acid. Each batch was analyzed to determine pH and concentrations of iron, sulfate, and manganese. The batches were divided into three groups based on composition of the simulated AMD (Table 1).

An argon atmosphere was maintained over the solution to prevent ferrous iron oxidation. Simulated AMD from each batch was split into four equivalent flows that were introduced into the base of each carboy (fig. 1). Upon entering the carboy, the solution contacted either a calcareous or a noncalcareous substrate and then flowed upward through the mushroom compost. An

Table 1. Composition of simulated AMD

Batch nos.	Average pH	Average batch composition (mg/L) iron	sulfate	manganese
1-7	4.8	89	310	-
8-12	4.3	91	328	44
13-20	3.2	100	394	49

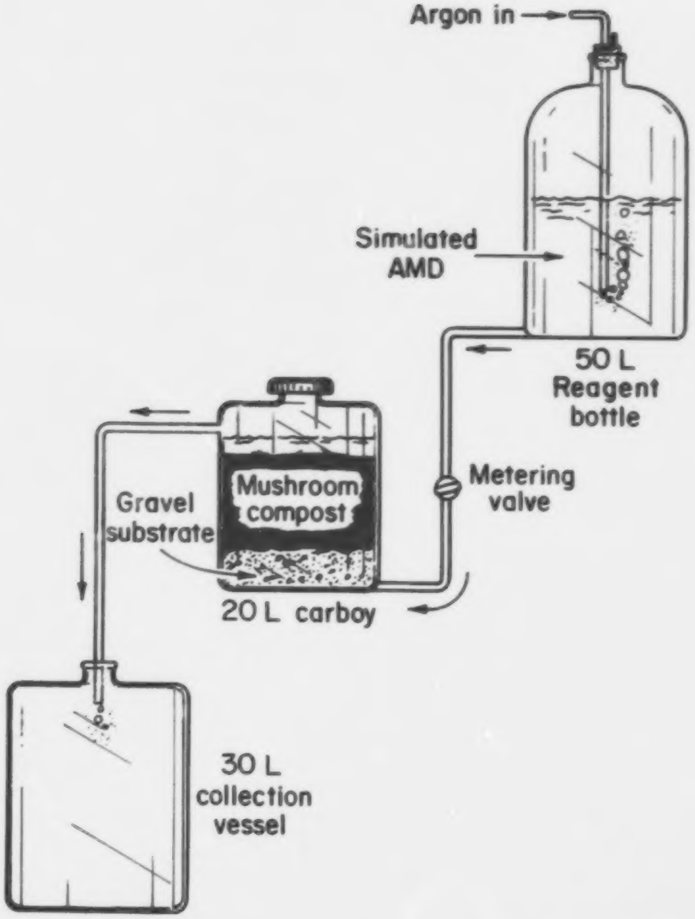

Figure 1. Sketch of sulfate reduction mesocosm.

outlet on the side of the carboy was positioned to maintain a water level about 5 cm above the top of the mushroom compost. Because the system was gravity fed, flow rates through each carboy varied between 90 and 150 mL/hr depending on the hydraulic head. Effluents from the four carboys were collected in 30 L glass bottles. At the end of each batch application, the volume of effluent from each carboy was measured and a sample analyzed for pH, alkalinity, iron, manganese, sulfate, and calcium. Acidity and alkalinity values were converted to $CaCO_3$ equivalent and reported as net alkalinity. Metal and sulfate loads were calculated for influent and effluent streams. Because the mesocosms were always kept inundated, the effluent for a particular batch contained, in part, effluent from the previous batch which had remained in the mesocosms between batch applications. Because of the carryover of effluents between batches, the response of the system to a change in influent water quality could not be fully evaluated until two batches had flowed through the system.

Results and Discussion

Upon the introduction of ferrous iron solutions, a pervasive, black, iron-monosulfide precipitate was observed to form throughout the mesocosms and in effluent lines. The distinctive odor of hydrogen sulfide was detected when the mesocosms were disturbed, although no hydrogen sulfide odor was noted under normal operation. The formation of iron sulfides and hydrogen sulfide with the concurrent removal of sulfate was taken as substantive proof that active populations of sulfate-reducing bacteria were established in each mesocosm.

pH and Alkalinity

Although the influent pH ranged from 4.8 to 2.5, the outflow from the mesocosms was consistently circumneutral (6.4 - 7.2), irrespective of the presence or absence of a calcareous substrate (fig. 2). The influent acidity (negative alkalinity), effluent alkalinity, and effluent calcium content were measured for batches 11 through 20. Figure 3 shows the average alkalinity of effluents from two mesocosms with calcareous material and two mesocosms containing no calcareous material. There is no difference in alkalinity between mesocosms with calcareous substrates and those without.

Calcium in the effluents was monitored (fig. 4) to determine if dissolution of calcium carbonate was responsible for the increase in pH and alkalinity. Calcium concentrations in the effluents of both calcareous and noncalcareous mesocosms were about equal, suggesting that the calcareous substrate was not the source of alkalinity. Therefore, the source of alkalinity must be either alkalinity naturally in the compost or alkalinity generated by sulfate reduction.

The neutralization potential (Sobek 1978) of fresh mushroom compost is about 35 tons $CaCO_3$ equivalent/1000 tons. Therefore, the alkalinity in each mesocosm, neglecting any contribution from sulfate reduction would be 140 g $CaCO_3$ equivalent. Because less than 100 g $CaCO_3$ equivalent of acidity were added to each mesocosm during the experiment, the initial alkalinity of the mushroom compost was not exhausted. Therefore, no estimate of alkalinity generation by sulfate-reducing bacteria can be made.

Iron

About 90 pct of the iron load was consistently removed upon passage through the mesocosms when the influent pH ranged between 4 and 5 (fig. 5). When the pH decreased to the 2.5-3.5 range, iron removal decreased to 78 pct and became more erratic. Overall, 86 pct of the iron was removed. The presence or absence of a calcareous substrate had no significant effect on iron removal efficiency.

Manganese

Starting with batch 8 (fig. 6), manganese was added to the simulated AMD. At pH 4.0-4.5, 80 pct of the manganese was removed by the mesocosms with calcareous substrates. For the same pH range, mesocosms with noncalcareous substrates removed only 64 pct of the manganese. At pH 2.5-3.5, manganese removal dropped to 52 pct in all mesocosms. Overall, throughout the course of the experiment, 57 pct of the influent manganese was removed. Manganese removal declined with each successive batch (fig. 6). When the experiment was terminated with batch 20, there was no clear indication whether manganese removal efficiency would continue to decrease or become constant (fig. 6). The overall effect of the calcareous substrate was also unclear. At pH 4.0-4.5, mesocosms with calcareous substrates exhibited higher manganese removal rates whereas at pH 2.5-3.5, calcareous and noncalcareous substrates were equally effective. More detailed work is necessary to determine the ability of anaerobic mesocosms to remove manganese.

Sulfate

Although sulfate removal was variable (fig. 7), the mesocosms averaged about 55 pct removal of influent sulfate. Slightly more sulfate was removed by mesocosms containing calcareous material, although the difference appears insignificant. Sulfate removal percentage was independent of influent pH between pH 2.5 and 5.0. The fact that sulfate removal continued even at low influent pH, suggests that sulfate-reducing bacteria may be active at a pH less than 4. This also suggests that the lower metal removal efficiencies observed at pH 2.5-3.5 may result from the increased solubility of metal sulfides rather than decreased rates of sulfate reduction.

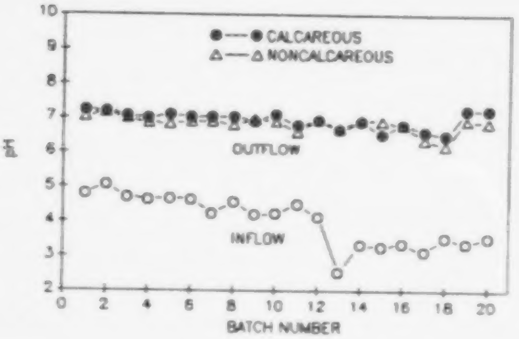

Figure 2. Plot of influent and effluent pH for anaerobic mesocosms with calcareous or noncalcareous substrates.

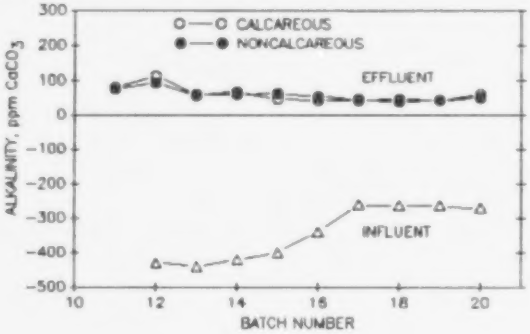

Figure 3. Plot showing change in alkalinity upon passage through anaerobic mesocosms with calcareous or noncalcareous substrates.

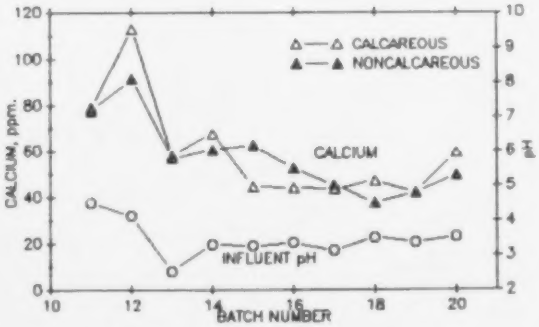

Figure 4. Calcium concentrations in effluents from anaerobic mesocosms with respect to substrate mineralogy and influent pH.

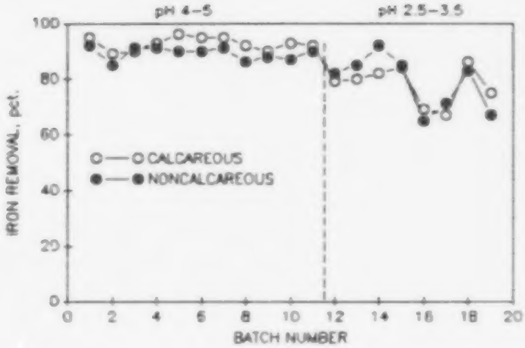

Figure 5. Iron removal with respect to substrate mineralogy and influent pH.

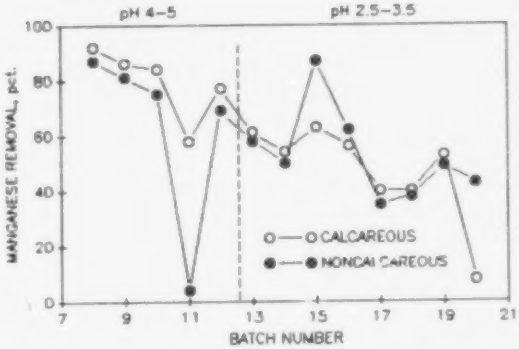

Figure 6. Manganese removal with respect to substrate mineralogy and influent pH.

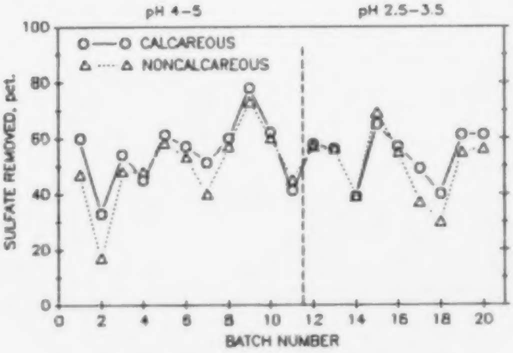

Figure 7. Sulfate removal with respect to substrate mineralogy and influent pH.

Relationship Between Metal Removal and Sulfate Removal

In figure 8, the millimoles of iron removed upon passage through the mesocosms is plotted versus the millimoles of sulfate removed. These points represent batches 1 through 7, before manganese was added to the simulated AMD and include data from calcareous and noncalcareous mesocosms. The least-squares regression line through these data has a slope of 0.67, and indicates that about 3 millimoles of sulfate are removed for every 2 millimoles of iron removed. Iron sulfide precipitates initially formed in sulfate-reducing systems exhibit a 1:1 stoichiometry of iron to sulfur (Berner 1984). With time, iron monosulfides react with elemental sulfur to form pyrite, which has a 1:2 stoichiometry of iron to sulfur. There are no known iron sulfides with the 1:1.5 iron to sulfur stoichiometry that is suggested by this plot. The two sulfides closest in stoichiometry are smythite and greigite, both with Fe:S ratios of 1:1.33. Obviously, not all sulfide is precipitated as iron monosulfide, even though iron is present throughout the mesocosms and in the effluents. Sulfide that is formed but not precipitated as FeS may: (1) escape from the mesocosm as H_2S; (2) be partially oxidized to form elemental sulfur; (3) be assimilated by bacteria or fungi; (4) form a disulfide mineral such as pyrite or; (5) be unable to compete with strong organic complexes for iron. The location of the y-intercept indicates that about 9 millimoles of iron are removed by reactions not related to sulfate removal. These reactions may include iron and substrate interactions such as adsorption, complexation, and ion exchange.

Figure 9 shows the millimoles of manganese removed with respect to the millimoles of sulfate removed. These points represent data from both calcareous and noncalcareous mesocosms for batches 8 through 20. Interpretation of this plot is complicated because the effect of iron on manganese removal is unknown. However, under these conditions one millimole of manganese is removed for every five millimoles of sulfate removed. It is clear that manganese removal is related to sulfate removal, although it is unknown whether the manganese is absorbed onto iron monosulfides or is precipitated as manganese carbonate or manganese sulfide. Sulfide and bicarbonate produced by sulfate reduction would promote the formation of manganese sulfide and manganese carbonate, respectively. Based solely on solubility considerations, the less soluble manganese sulfide (pKsp = 13.27) would probably predominate over manganese carbonate (pKsp = 10.4). The species kinetically favored is not known at present. The removal of about 3 millimoles of manganese (y-intercept) is unrelated to sulfate reduction.

Conclusions

Results of this experiment indicate that ecosystems of sulfate-reducing bacteria growing in spent mushroom compost remain

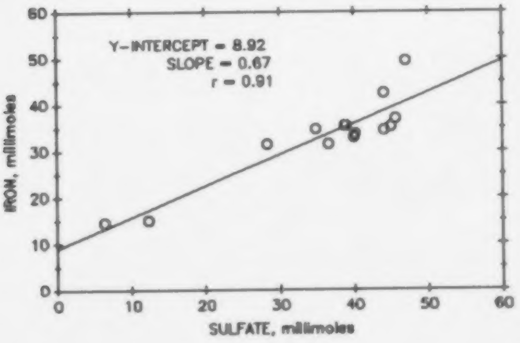

Figure 8. The relationship between iron and sulfate removal.

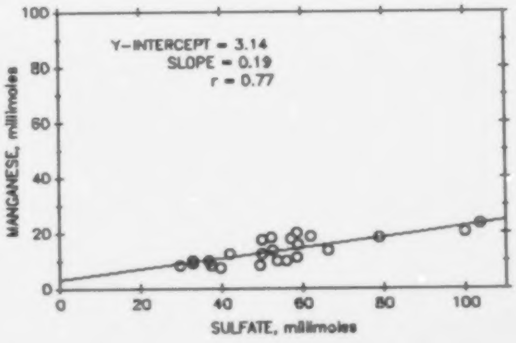

Figure 9. The relationship between manganese and sulfate removal.

active when simulated AMD with a pH as low as 2.5 is introduced into the system. Because of the natural alkalinity of mushroom compost and the alkalinity generated by sulfate reduction, it is not known if sulfate-reducing bacteria were actually contacted by low-pH waters. Water quality was significantly improved upon passage through the mesocosms. About 78-90 pct of the iron and 64-80 pct of the manganese were removed from simulated AMD at influent pH 2.5-5.0. Iron and manganese removal efficiency decreased at lower pH probably reflecting the increased solubility of metal sulfides. Manganese removal efficiency decreased with time even at a constant influent pH. The system lowered influent sulfate concentrations by 50-60 pct and resulted in an effluent of circumneutral pH. The effluents from these ecosystems were alkaline despite an influent acidity between 220 and 430 mg/L $CaCO_3$ equivalent. The presence or absence of a calcareous substrate did not make any significant difference in the amount of iron or sulfate removed nor did it affect the pH or alkalinity of the effluents. At influent pH 4-5, manganese removal was higher in mesocosms with calcareous substrates. However, at pH 2.5-3.5, the manganese removal in mesocosms with calcareous substrates did not differ from that of mesocosms with noncalcareous substrates. Results of these experiments indicate that the calcareous substrate conventionally used in constructed wetlands is unnecessary for sulfate reduction unless manganese removal is a major concern.

Future Work

Future work will concentrate on determining if sulfate reduction will continue in the presence of AMD after the natural alkalinity of mushroom compost is exhausted. The ability of a sulfate-reducing ecosystem to generate alkalinity will determine the long-term feasibility of using a sulfate reduction strategy for treating AMD. Further work is necessary to determine:

1. the optimum system configuration,
2. the minimum pH and maximum metal concentrations tolerated by an active fermentative/sulfate-reducing ecosystem,
3. the organic substrate requirements,
4. the optimum flow rates and residence times, and
5. the metal loading capacity for each metal.

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Bacterial Acid Generation in Pyritic Shales and Remedial Measures[1]

by

R.G.L. McCready[2]

Abstract Since the isolation and identification of Thiobacillus ferrooxidans by Colmer and Hinkle in 1947, numerous investigators have tried to develop techniques to prevent bacterial acid generation within pyritic mine wastes. To date, none of the techniques developed have been completely successful. During the construction of a taxiway at Halifax International Airport in Nova Scotia in 1982, about 225,000 cubic meters of fractured waste pyritic slate material was disposed, on site, in a pile covering about 7 hectares. As a result of air and water infiltration and the presence of indigenous Thiobacillus ferrooxidans, this waste rock pile has been seeping a metal laden acidic effluent similar to acid mine drainage. As sufficient quantities of a relatively impermeable clay overburden were present on site , it was decided to apply a compacted clay cap to the pile to reduce air and water infiltration. From previous experience it was known that concentrations of sodium chloride, greater than 1% in the aqueous phase, were inhibitory to Thiobacillus ferrooxidans. Laboratory studies confirmed that the addition of a layer of highway salt beneath the clay layer not only prevented the formation of acid mine drainage, but also enhanced the sealing capacity of the clay. Capping of the waste rock pile was completed in 1987, and the results to date will be presented.

Additional Key Words: Thiobacillus ferrooxidans, clay covers, pyritic slate, rock salt.

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[1] Paper presented at the Reclamation, A Global Perspective, held in Calgary, Alberta, Canada August 27 - 31, 1989.

[2] R.G.L. McCready is head of the Biotechnology section at CANMET, Dept. of Energy, Mines and Resources Canada, in Ottawa, Ontario, Canada. K1A 0G1

Introduction

Halifax International Airport is located on a band of highly mineralized pyritic bedrock. During airport expansion, 225,000 m^3 of waste rock was excavated and stockpiled over a 7 hectare area. Several months after disposal, an acidic effluent laden with metals began seeping from the waste rock pile and from the taxiway subdrains. A water collection system was built and all effluents were treated by lime addition at a water treatment plant. At the time, it was thought that the acidic drainage would subside with time.

When the acidic seepage continued, unabated, for five years, a decision was made to place an impermeable seal over the waste rock pile to prevent infiltration of air and water. An interdepartmental technical committee was struck to advise Transport Canada on the "state of the art" in the control of acid mine drainage. The committee charged the Canada Centre for Mineral and Energy Technology (CANMET) to investigate the feasibility of incorporating a salt layer between the clay cap and the pyritic waste slate. This paper describes the results of the laboratory investigations and the effect of the clay/salt capping of the pile to date.

Bacterial Acid Generation

Thiobacillus ferrooxidans is an autotrophic, acidophillic organism which grows in the pH range of 1.8 to 3.0. Cellular carbon is obtained from atmospheric carbon dioxide and the cell obtains all of its energy requirements from the oxidation of ferrous iron to ferric iron as well as the oxidation of sulphides to sulphate. The cells are rod shaped (0.5 um x 1 um), have a polar flagellum for locomotion in liquid media and produce pili (fimbriae) on the external cell wall for attachment to surfaces(Figure 1).

The microbiological oxidation of pyrite at pH 1.91 is represented by the following equation (Ahonen et al, 1986):

$$FeS_2 + 3.75\ O_2 + 0.5\ H_2O \rightarrow Fe^{3+} + SO_4^{2-} + HSO_4^-$$

Recent studies have shown that the organisms bind exclusively to the mineral sulphide phases of metal containing ores and totally ignore the non-sulphidic gangue material (Bennet and Tributsch, 1978; Sanmugasunderam et al, 1988).

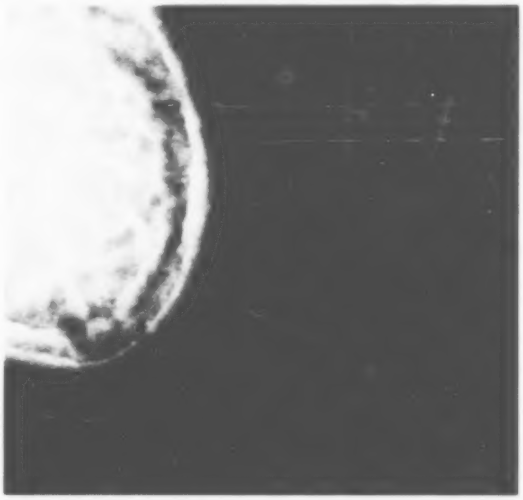

Figure 1: Electron micrograph of *Thiobacillus ferrooxidans* (x 170,000).
Note the large polar flagellum and the hair-like pili on the cell surface.

During the oxidation of metal sulphides the organisms produce extensive pitting of the mineral sulphide crystals and often extensive chemical precipitates of ferric hydroxide or various ferric jarosites occurs within these bacterially produced pits (see Figures 2 and 3).

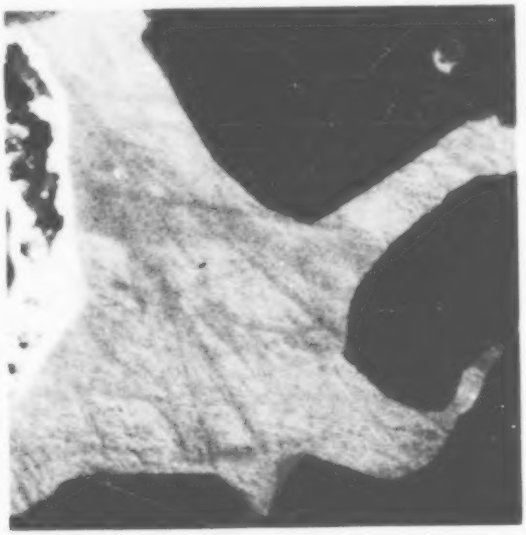

Figure 2: Pitting of a polished ore surface due to the bacterial leaching of sphalerite.

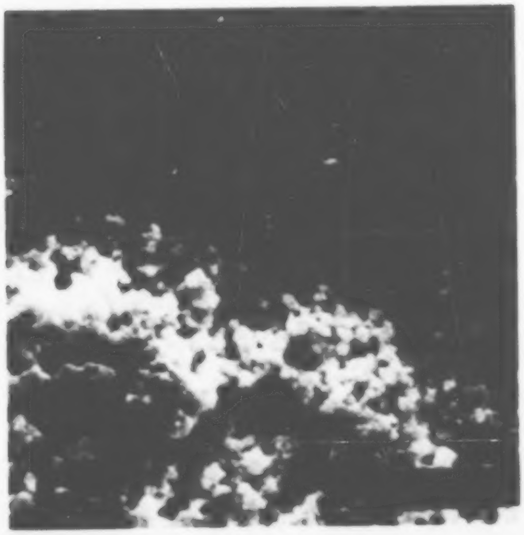

Figure 3: Scanning electron micrograph of the chemical precipitates seen in the pits produced by bacterial leaching of mineral sulphides.

Laboratory and Field Tests on Capping

CANMET set up laboratory leaching columns (6cm in diameter and 50cm long) to test the effects of a clay/salt cap, a clay cap and a control column.For this study, 1kg of clay was used which was tightly compacted and 250ml of distilled water was added to the columns to assess the percolation rate through the clay. The clay used in these studies and at the airport is described by the Unified Soil Classification System (USCS) as Silty, Sandy Clay and Sandy, Silty Clay. Its measured permeability was 4 x 10^{-7} cm/sec. Highway rock salt addition was based on assumed pore space within the pile being 40% void volume.

Sufficient salt(approx. 5g) was added as a layer between the waste slate and the clay cap to produce a 1.5% w/v solution of sodium chloride in the interstitial water if a rupture in the clay seal allowed the infiltration of water (McCready and Krouse, 1982,1982a)

Table 1 Metal content of the Halifax Slate (Murray et al.,1988)

Element	Percentage	mg/g
Aluminum	9-13	
Iron	3-6	
Manganese	0.01-0.04	
Cobalt		10-80
Nickel		40-270
Lead		10-48
Arsenic		4-19
Copper		18-46
Zinc		70-21

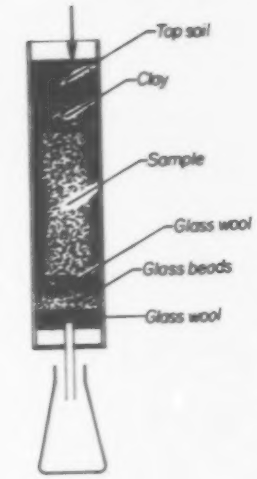

Figure 4: Schematic drawing of a laboratory test column.

From the column study, the iron content of the seepage in the clay and salt capped column declined from 292 mg/L to 34 mg/L and the pH of the interstitial water remained at 2.51. Over a period of three months, although a head of water was applied to the column, no water penetrated through the clay/salt cap. When the cap was allowed to dry out, horizontal cracking was observed, rather than the vertical cracking observed in the clay only cap.

After drying the caps out, water was reintroduced and 4.9L. percolated through the clay only capped column over a four month period. However, on rewetting the clay/salt cap, it immediately resealed itself and no water penetration into the column was observed over a four month period.

Due to the success of the laboratory study, the waste rock pile at the Halifax Airport was recontoured to allow all precipitation to flow off the surface, a layer of road salt was spread over the surface and subsequently sealed with two lifts of 300 mm of compacted clay. The clay cap was then covered with 150 mm of top soil and seeded to grass and the slopes were sodded. The total cost for the 7 hectares was $800,000.

Prior to capping, the waste rock pile produced a constant drainage of about 200 gpm, with acidities as high as 7800 mg of acidity/L, ferric iron concentrations of 1200 mg/L and aluminum contents as high as 700 mg/L. At the end of 1988 the volume of drainage varied from 25 to 50 gpm, the acidity is consistently below 900 mg/L, and the metal contents have declined substantially. Iron is consistently below 40 mg/L and Aluminum is generally <50 mg/L. Because of the low pH and the high heavy metal content the water was treated in a Lime neutralization plant to precipitate the heavy metals and adjust the pH before releasing the water to the environment.

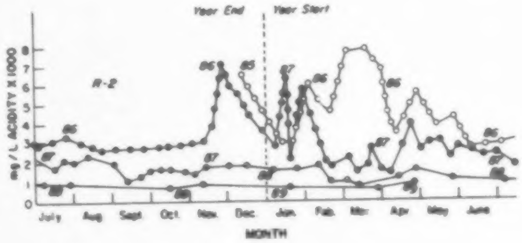

Figure 5: Acidity of influent to water treatment plant vs. time.

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Mine Tailings Reclamation Symposium

Session Chairman: S.A. Bengson

THE EFFECT OF FREEZING AND THAWING ON THE DEWATERING OF OIL SANDS SLUDGES[1]

by

Richard L. Johnson[2], Peter Bork[3], Paul Layte[2]

Abstract. Oil sands processing operations in northeastern Alberta generate 25 x 10^6 m^3 of water-fines mixtures (sludge) per year. The fines settle in several weeks but will not consolidate to more than 35% solids, even over centuries. Freezing and thawing the oil sands sludge led to rapid dewatering. One cycle of freezing and thawing caused 15, 25, 35, and 45% solids sludge to reach 35, 39, 48, and 51% solids content, respectively. Subsequent freeze-thaw cycles, up to a total of three, caused less rapid increases in solids content. The maximum concentration of solids by freezing and thawing, even after repeated cycles, was 60%. The amount of dewatering due to freeze-thaw can be confidently predicted by knowing only the initial solids content. The freezing time for each sludge concentration was monitored to compute proportionality coefficients required to predict freezing depths under field conditions.

Additional Key Words: slurries, tailings, Neuman-Stefan proportionality coefficient, solids concentration.

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[1] Paper presented at the 1989 International Symposium on Reclamation, A Global Perspective, sponsored by the Canadian Land Reclamation Association and the American Society for Surface Mining and Reclamation, Calgary, Alberta, August 27-31, 1989.

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Introduction

The enormous volumes of oil sands tailings generated by two extraction and upgrading plants located near Ft. McMurray, Alberta, pose economical and ecological problems in land reclamation. Approximately 170,000 barrels of synthetic oil per day is produced from 400,000 tonnes of oil sands; the tailings stream amounts to 180 million metric tonnes per year and currently occupies 25 km².

Sludge, a mixture of fines (<22 microns diameter), water, and residual bitumen, is the most difficult component in the tailings stream to handle for reclamation. The sand portion of the tailings stream segregates from the slurry upon deposition at the edge of the tailings pond and is used to build the pond dikes. Thin sludge, at approximately 5% solids content, flows into the pond and settles to a solids content of 20 to 30% within two years. The sludge volume now exceeds 250 million m³ and is increasing at the rate of 20 million m³ per annum. Consolidation to 80% solids, representing a firm, stable surface, is expected to take tens of thousands of years if left to mature under natural conditions (Scott et al. 1985).

The most recent research at the Alberta Environmental Centre explores the possibility of using vegetation to dewater relatively thin layers of sludge (<3 m) through evapotranspiration (Johnson et al. 1989). Two species of hydrophilic plants, reed canary grass (Phalaris arundinaceae) and dock (Rumex occidentalis) have proven successful on a small scale. However, to establish plants quickly and achieve complete dewatering in one summer, a bed of at least 50% solids sludge is needed. Among the alternatives to increase the solids content of oil sands sludge from 30% to 50%, dewatering by freezing and thawing appears to be most efficient and economical.

Freeze-thaw originated as a dewatering technique in temperate climates where biological sludges were concentrated from 3-5% solids to >30% solids (Downes, 1939, Clements et al. 1950, Bishop and Fulton, 1968, Logsdon and Edgerly 1971, Rush and Stickney 1979). Preliminary tests on the effect of freeze-thaw on oil sands sludge caused a large increase in percent solids (Johnson et al. 1989). Since Ft. McMurray has long, cold winters, freezing and thawing could be a low cost, efficient means of dewatering oil sands sludge on a field scale.

To develop a rational engineering procedure for freeze-thaw dewatering, the environmental factors that control frost penetration must be quantitied (Martel 1989). The Neuman-Stefan formula for predicting the formation of ice on lakes should also apply to liquid sludges (Reed et al. 1986). This formula requires information on the freezing index of a location (Rush and Stickney 1979) and a proportionality coefficient for the material being frozen or thawed, which depends upon its thermal conductivity and latent heat. One objective of the research described here is to calculate a Neuman-Stefan coefficient for oil sands sludge.

Materials and Methods

This freeze-thaw experiment on oil sands sludge was carried out under pilot plant scale conditions: experimental units were barrels with a capacity volume of approximately 60 L; sludge was diluted with water to four solids contents using a rotor attached to an electric drill; the sludge was frozen by placing the barrels inside a walk-in freezer and thawed by removing them from the freezer and letting them stand in a open work space.

Experimental Units

The experimental units were constructed by placing an interior metal drum into an exterior polyethylene drum (Figure 1). To simulate natural freezing conditions, where the freezing front progresses from the surface downward, insulation was inserted between the two containers and at the bottom of the inside barrel. A total of 12 experimental units were constructed to allow three replicates of four sludge dilutions.

Sludge Dilution Mixes

Four sludge dilutions were chosen to represent a wide range of solids contents in the oil sands tailings ponds: 15, 25, 35, and 45% (solids, dry weight basis). These were prepared by sequentially diluting a batch of high solids content sludge with reverse-osmosis, deionized water. After completing each dilution, three experimental units were filled to a depth of 46 cm providing an initial volume of 45 L. Sludge sampling inside the experimental units was conducted prior to initial freezing and after every freeze-thaw cycle. All replicates were sampled at three depths: one-sixth, one-half and five-sixths of the total sludge depth. The sample sites inside the experimental unit were selected randomly, using a random number table where each number corresponded to a grid intersection placed over the sludge surface. The percent solids of the samples were determined by mass measurements before and after oven-drying (105°C for 24 h).

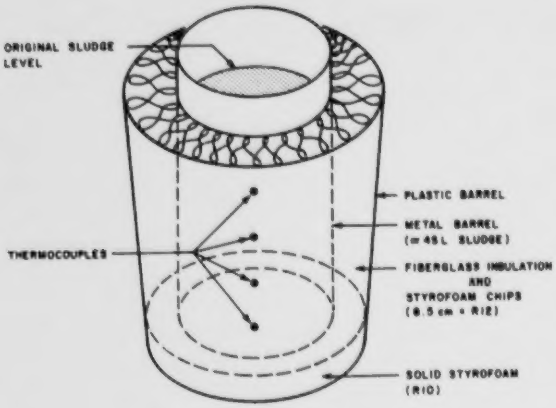
ORIGINAL SLUDGE LEVEL
THERMOCOUPLES
PLASTIC BARREL
METAL BARREL (≈ 45 L SLUDGE)
FIBERGLASS INSULATION AND STYROFOAM CHIPS (8.5 cm = R12)
SOLID STYROFOAM (R10)

FIGURE 1. EXPERIMENTAL UNIT FOR FREEZING AND THAWING OILSAND SLUDGE PLACED INSIDE AN INSULATED BARREL

Freezing and Thawing

The twelve units were placed in a completely random pattern inside the freezer. Unit location was randomized each time the freezing cycle was repeated. The freezer temperature was kept at -24°C throughout the experiment. One replicate of each sludge dilution was fitted with four type T thermocouples connected to a Campbell Scientific CR 10 micro-logger (Figure 1). Temperatures were recorded at four depths within each sludge dilution mix. When each thermocouple within the frozen sludge registered a maximum temperature of -20°C, the freezing period was considered complete. All units were removed from the freezer at the same time for the thaw stage.

Two days into the thaw period the units were covered with lids to prevent moisture loss by evaporation. The thaw period was considered complete once all units registered a minimum temperature of 20°C. The surface bitumen was skimmed off, and the thaw water was removed and measured volumetrically. The experimental units were then sampled for solids contents in the manner described above.

The freeze-thaw process was repeated three times.

Freezing Coefficient Determination

The Neuman-Stefan formula allows for the calculation of total freezing depth (Reed et al. 1986):

$$x = m\,(\Delta T \cdot t)^{1/2} \qquad (1)$$

where:

x = depth of freezing [cm],
m = proportionality coefficient depending on the thermal conductivity, density, and latent heat of the material being frozen [cm/(°C.day)$^{1/2}$]
$\Delta T.t$ = freezing index [°C.day],
ΔT = difference between the freezing temperature and average daily ambient temperature [°C],
t = time period of concern [days].

By rearranging the formula the proportionality coefficient for oil sands sludge can be estimated:

$$m = \frac{x}{(\Delta T \cdot t)^{1/2}} \qquad (2)$$

The fourth thermocouple, placed at approximately 8 cm above the bottom of the sludge, was used as the freezing depth to calculate the proportionality coefficient from equation 2. Only data from the first freeze-thaw cycle was used in this calculation.

Results

The sludge concentrations before and after each freeze-thaw cycle are given in Table 1. Individual values represent the average of samples taken at three depths within three replicates of each mix. (The exceptions to this are one replicate each from mixes 1 and 2, representing 45 and 37% solids, respectively. In both cases the metal drums failed due to pressures exerted during the freezing cycle).

There were some small differences between the intended and actual solids contents, but the largest variance was only

2.4% (mix 2 was intended to be 35% and, in fact, reached 37.4%). Overall, the desired range of solids content was achieved.

Table 1. Average percent solids before and after freeze-thaw cycles.

Mix #	Original Solids Content (%)	Solids After Freeze-Thaw Cycle 1 (%)	2 (%)	3 (%)
1	45.4	51.3	57.8	60.4
2	37.4	47.9	55.1	59.6
3	26.2	38.7	46.4	52.6
4	16.3	35.4	46.2	49.5

While each freeze-thaw cycle resulted in a progressive dewatering of each mix, it is apparent that the first cycle was more effective than the second which, in turn, was more effective than the third (Figure 2). And even more noticeable is the effect of initial solids content on the amount of dewatering. Mix 1, starting at 46% solids, had a cumulative increase of only 35% over three freeze-thaw cycles; mix 4, on the other hand, starting at 16% solids finished after three cycles at 49.5% solids, a 200% cumulative increase! The two intermediate dilutions also had intermediate cumulative increases in solids content (Figure 2), indicating a correspondence between initial and final solids content.

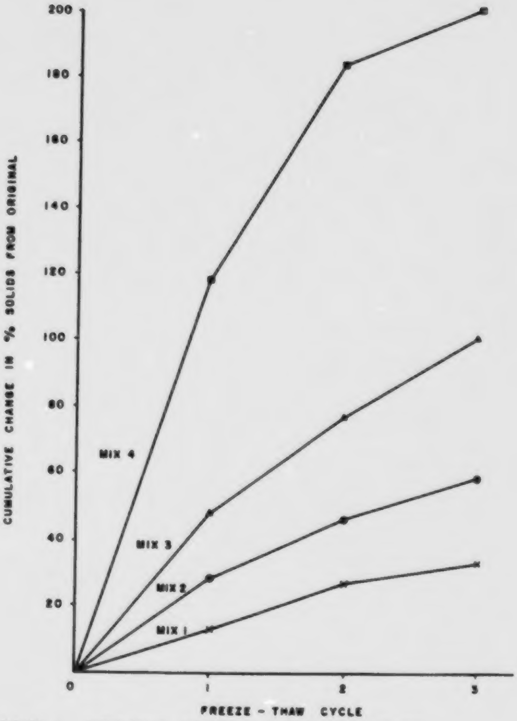

FIGURE 2. CUMULATIVE INCREASE IN % SOLIDS THROUGH 3 FREEZE-THAW CYCLES

The relationship between initial solids content of oil sands sludges and the degree of dewatering through freeze-thaw cycles is exponential (Figure 3). Low initial solids content results in a large amount of dewatering. As the solids content increases the rate of dewatering drops quickly. The exponential decrease in rate of dewatering is independent of freeze-thaw cycle, which acts only as a determinant of "initial" solids content. The prediction of final solids content of oil sands sludge undergoing freeze-thaw can be confidently made without considering the previous freeze-thaw history of the sample:

$$Y = 365.3\ (0.93)^{x} \qquad (3)$$

where:

Y = final solids content [%]
x = initial solids content [%]

The coefficient of determination (r^2) is high - .95. Only 5% of the variation in final solids content is not accounted for by the initial solids content.

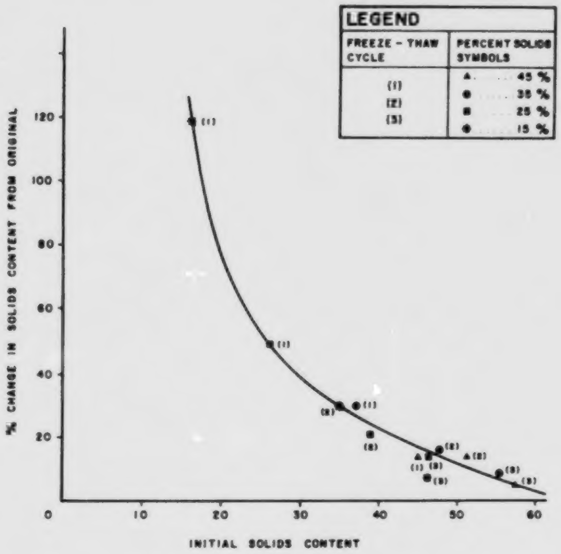

FIGURE 3 CHANGE IN FINAL SOLIDS CONTENT IN RELATION TO INITIAL SOLIDS CONTENT AND FREEZE — THAW CYCLE

The relationship between the initial solids content of the sludge and the calculated Neuman-Stefan proportionality coefficients are given in Table 2. For mixes with solids contents less than 45%, there is a linear relationship between the Neuman-Stefan proportionality constant (m) and the initial solids content such that:

Table 2. Neuman-Stefan proportionality coefficients for oils and sludge mixes.

Original solids content (%)	Freezing Time hours	Freezing Time days	Proporttionality constant (m)
45.4	125	5.2	3.41
37.4	177	7.4	2.86
26.2	195	8.1	2.73
16.3	217	9.0	2.59

$$m = 0.0128\ x + 0.998 \qquad (4)$$

where:

x = initial solids content [%]

The coefficient of determination is 0.996. For the mix with an initial solids content of 46%, the proportionality coefficient is much higher than that which might be predicted by equation 4.

Discussion

The experimental results confirm previous findings at the Alberta Environmental Centre that the freeze-thaw process increases the solids content of oil sands sludge (Johnson et al. 1989). The mineral fines originating from bitumen extraction processes have less than two percent organic contents (Scott et al. 1985), but act like sewage sludges when subjected to freeze-thaw conditions (Rush and Stickney 1979). The sludge mixtures with the lowest solids content, mineral or organic, dewater to the greatest extent. There is an exponential decrease in the amount of water released as pre-freezing solids contents increase. Multiple freeze-thaw cycles cause progressive loss of water, but the same exponential relationship between original solids contents and amount of water loss applies. That is, the second and third and more freeze-thaw cycles are acting on mixtures with higher and higher solids contents and, therefore, there is an exponential decrease in the amount of water lost with each cycle.

The oil sands sludges tested in this experiment reach a maximum of approximately 60% solids contents, if subjected to enough freeze-thaw cycles (Table 2, Figure 3). On an operational basis the sludge accumulating at the bottom of the tailings pond on the Syncrude Canada Limited lease reaches a maximum of 35% solids in two to five years; according to equation 3 and Table 2, one winter of freezing and thawing will yield sludge at 45% solids content. This has been corroborated in a recent field experiment conducted in Ft. McMurray (Johnson et al. 1989).

One proposed reclamation scheme for oil sands sludge involves the use of plants to dewater sludge through evapo-transpiration. To successfully establish plants a relatively firm seed bed is needed, corresponding to approximately 50% solids content. One winter will produce the desired seed bed conditions, a sludge surface at 45-50% solids, depending on the depth of sludge frozen, the type of drainage employed, and the amount of moisture lost through evaporation prior to the establishment of the plants.

The proportionality coefficients for the Neuman-Stefan formula have a linear relationship to the original solids contents. This formula is used to estimate the depth of freezing achievable in a selected time period (Reed et al. 1986) and can now be used confidently to design facilities and treatment programs for oil sands sludges, where the thickness of individual layers and the time periods for freezing are critical constraints. Work is currently underway at the Alberta Environmental Centre investigating a dynamic (multiple layers) freeze-thaw process for oil sands sludges.

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OVERVIEW OF TAILINGS RECLAMATION IN EASTERN CANADA

by

T. H. Peters

Abstract An overview of the climate, topography, and the various factors associated with the production of minerals in Eastern Canada as they impact on mine tailings reclamation.

Additional key words: Eastern Canada, mine tailings, reclamation.

Introduction

The wide and diversified range of metals mined in the mineral producing provinces of Ontario, Quebec, New Brunswick Nova Scotia and Newfoundland represented 35% Of the total value of mineral production in Canada in 1986. The production which accounted for the other 65% of the total value was mainly attributable to the hydrocarbon production of the Prairie Provinces (Manitoba, Saskatchewan and Alberta) and British Columbia.

The production by provinces in Eastern Canada and the number of producing mines/ mills is shown in table 1. It is of interest to note that 1 province, Prince Edward Island is the only non-mineral producing province in Canada and it is located in Eastern Canada.

Mine tailings in Eastern Canada include a wide range of waste types and conditions. Mining of lead, copper, zinc, nickel, gold, uranium, silver, iron, and other minerals have produced a variety of tailings wastes with unique characteristics. Table 2 shows the distribution of these areas in Eastern Canada. The area of tailings from both active and closed mining operations is included as well as the extent of the area which has been vegetated or reclaimed as of 1975. This survey of mine wastes made in 1975 by CANMET indicated that there were 10,372 hectares (25,629 acres) of tailings in Eastern Canada of which 919 ha (2,271 acres) had been stabilized with some form of vegetative cover. It is of interest to note that this area of tailings occupies approximately 0.036% of the total area ofthe 6 eastern proivinces. At the time of the survey, mine waste stabilization was just beginning to be generally accepted. A large part of the stabilized tailings could be attributed to natural vegetation encroachment and the reclamation efforts of a few progressive mining firms.

The earliest reclamation work in the east was in 1932 in Timmins, Ontario, when the McIntyre-Porcupine Company converted their first tailings disposal site into a park. The next major development in vegetating tailings was the work started in the mid 1950's by Inco Limited in the Sudbury area with their successful establishment of grass and legumes on sulphide tailings.

By the mid 1970's an increasing number of test plots began to appear on different tailings areas in Eastern Canada and plant growth trials were initiated in various laboratories and green - houses. These experiments,carried out by a few part-time and full-time reclamationists, began to provide input into the literature on the ways and means of addressing tailings vegetation in the Canadian situation. The foresight of the various companies in underwriting the costs associated with this research at a time when there was little or no public pressure reflected then and continues to reflect to their credit.

Gold, silver and iron tailingsappeared to present little chemical difficulty to vegetation establishment. Local climatic conditions, such as the growing season, precipitation distribution, and wind direction were the predominant problems facing the reclamation of these wastes. Stabilization of the tailings surface and the addition of plant nutrients provided the neccessary conditions for the establishment of the early grasses and legumes. With the sulphide containing wastes of the copper, nickel, zinc, lead and uranium mines, attention was also directed towards alleviating the harmful chemical conditions inherenlty present. The addition of lime, other alkaline tailings, topsoil, rock barriers, and chemical sealants were used to nullify the impact of the reactive nature of these tailings.

Research continued to find the answers to the many problems confronting the people actively involved in the reclamation of these wastes. In the late 1970's, both the federal and the provincial goverments became increasingly involved in developing legislation regarding the stabilization and the revegetation of areas covered with mine tailings to minimize their impact on the environment.

Ecological Situation

With the exception of the coal mining operations in the Maritime Provinces of Eastern Canada, the major mining operations are located in the Precambrian Shield.

The major portion pf the topography can be classified as undulating with valleys between rounded hill tops. Glaciation in the late Pleistocene era was responsible for many of the geomorphic formations and soil types in the Shield area. The land was heavily scoured and much of the soil removed with the result that numerous rock outcrops were and remain exposed.

The generally harsh climate in the mining areas of Eastern Canada with the short number of frost free days and long cold winters has inhibited the rate of soil development. Soil flora and fauna are active in most areas less than half of the year. The physical forces brought into play by the alternate cycles of freezing and thawing with the associated expansion and contraction of the mineral material, has been a major factor in breaking down the rock to particle size.

Compared to the rest of the world, the formation period of the present soils in Canada has been short. Most of the material was transported by ice or water as recently (in geological time) as the Wisconsin period of the Pleistocene era to its present site.

In general the ecological factors have combined to develop a podsol type soil with glacial surface deposits of water modified tills, lacustrine silts and sands located in the valleys.

Reclamation

The developing of a park on their first tailins disposal site by McIntyre Porcupine in 1932 initiated tailings reclamation in Canada. Their method was to cover the tailings with soil and establish an appropiate planting of grass, trees and shrubs. Other gold mines in the Tim- mins, Ontario, area subse- quently started reclaiming their tailings dumps in the 1960's. Herman Keller pioneer- ed in developing low mainten- ance vegetation covers involv- ing legumes in this same area. Since the tailings were mainly silica from the waste quartz in the ore, he was able to develop a program for direct seeding into the tailings.

The base metal mines and uranium mines in New Brunswick Quebec and Ontario were faced with the problems of mining sulphide ores and the consequent acid generating potential and low pH levels of their tailings. Negative results from early attempts at establishing vegetation on their tailings in the 19940's at Inco Limited in Sudbury directed the Company's research efforts to other methods of dust control such as sealants and water sprays. These proved ineffective and costly. Small scale investigations into methods to establish vegetation on the tailings were resumed in the early 1950's. The procedures developed from this start will be discussed later in the paper.

In the late 1960's Drs. E.Watkin and Jack Winch of the Crop Science Department, Ontario Agricultural College of the University of Guelph were involved in a project sponsored by the Ontario Cover Crop Committee to improve low grade rough pastures for livestock production. Their interest in the research to improve the vegetative cover on rough pasture land in Northern Ontario soon broadened to include the problems associated with establishing a vegetative cover on tailings. Before long, they initiated a field test plot program on the uranium tailings at Elliot Lake.

In the early 1970's, the first major research program into developing the requirements and methods to establish vegetation on sulphide tailings was started in the Crop Science Department at the University of Guelph. This five year program was funded and sponsored by Noranda Mines Limited and was under the full time direction of Dr. Edward Watkin. Amongst other things, this research proved the necessity of including legumes in tailings revegetation programs. The superiority of Birdsfoot Trefoil (*Lotus corniculatus L.*) as the legume for this purpose was established.

Other than Inco Limited, the mining companies in Eastern canada did not have the in house capabilities or equipment for undertaking reclamation revegetation. These companies had to turn to outside contractors to carry out this work. Erocon Limited of Timmins, Ontario, founded by Herman Keller and Dol Brothers of Cookstown, Ontario, founded by J.Dol developed and contributed, through their interest in this work, their ingenuity, and their understanding of the special factors involved in seeding tailings, much of the knowledge along with many of the practices currently in use.

Case Studies

The original approach to revegetation on the 3 sites reviewed is similar. However, somewhat different approaches to handling the problems associated with acid generation in tailings are evolving at the different sites.

The history and practices followed in the current Inco Limited tailings reclamation program since its inception in the early 1950's have been the subject of numerous papers in recent years (Peters, 1985).

The experience gained over the past 35 years, both positive and negative, has resulted in the formulation of the following guidelines. These, in general, are applicable to most sites in Eastern Canada.

1. The first seeding in the tailings area should be located in the portion closest to the prevailing winds during the growing season to minimize damage

to or covering of the young plants by drifting wind borne tailings.

2. Agricultural limestone, as required, should be applied and worked into the surface prior to seeding. The major portion should be applied at least 6 weeks before seeding. This permits sufficient time for the reaction to raise the pH of the tailings to 4.0-5.0. The balance should be applied immediately prior to seeding.

3. In the Sudbury area, the late summer is the best time to seed grasses. After July 21, the rate of success of seed germination and seedling establishment is enhanced due to more favourable temperatures and increased availability of moisture from precipitation.

4. Although the late summer is the optimum time for seeding grasses, the short period remaining in the growing season, is insufficient for legume seedlings to establish a sufficiently deep and strong root system to withstand the heaving effects of the repeated freezing and thawing of the tailings surface the following spring.

5. The use of a companion crop to provide shade and reduce the velocity of the surface winds is essential.

6. Nitrogenous fertilizer should be applied, at low but sufficient rates, several times as required, during the establishment period to ensure maximum uptake.

7. The surfacing of the slopes with south and southwesterly exposure with 15 cm. (6") of clay to ensure an adequate supply of moisture for growth is worthwhile.

8. The use of a mulch on the slopes, preferably one containing straw, to provide shade for the seedlings and to reduce the evaporation of soil moisture during the critical period of seedling establishment is worthwhile.

9. When clay is used to surface rhe outside slope of a tailings dam, the whole slope should be covered from top to bottom. The addition of a clay topdressing on a tailings slope will physically reduce the porosity of the slope's surface. In all cases, it is essential to maintain the structural integrity of the dam and no treatment which will change a dam's structural strength should be employed in revegetation. If required, adequate diversion ditches for the safe drainage of the slopes should be included as part of the surfacing program.

The presence of tree seedlings which were voluntarily establishing themselves in the newly grassed areas became very apparent in 1964. This indicated that the first step had been taken in establishing a climax vegetative cover similar to the original cover.

Several tree plots to assess the adadaptability of different species were set out. Based on the information gained from these plots a full scale program was developed for the planting of coniferous species. Currently many of the tree seedlings used in this program are grown 4600 feet underground at the Creighton Mine. Field experiments to assess the potential of mixed plantings with species that possess the capability to fix atmospheric nitrogen are underway in cooperation with the federal government.

In 1974 a plan to develop a Wildlife Management Area on the tailings as a possible end use was initiated. Various testing programs to assess any impact on the food cycle and life cycle of species which might inhabit this eventual forest cover and ponds were carried out. Many were undertaken by students in graduate courses at Laurentian and other Ontario universities. Results indicated that this was a worthwhile program and the first steps to introduce a flock of Canada Geese (Branta canadensis) were taken in 1985 with the introduction of 70 fledglings. Many of these, and subsequent annual introductions, have returned each year during the spring migration and several have brought back mates with whom they have raised families.

Falconbridge Limited, like many other Canadian mining companies, has successfully established grass and legume vegetative covers on tailings areas (Michelutti, 1975). Unlike most companies, Falconbridge has utilized overburden material as a reclamation technique to prevent the upward migration of metallic salts, and minimize water infiltration (Spires, 1975; Michelutti, 1978). It is evident that in some instances these vegetative covers have not completely eliminated acidic, metal contaminated seepages.

Falconbridge's overall objective is to establish a methodology that will allow companies to walk away upon abandonment of a tailings area, with no further treatment required. One method to do this is to prevent the oxidation of the pyrrhotite and sulphur wastes that ultimately generate sulphuric acid. To minimize or prevent this oxidation, various covers are currently being investigated.

The types of covers being investigated are firstly dry covers and secondly wet covers.

Two different dry covers are under test at their Fecunis Tailings Area. The first consists of a 2 m. thick layer of waste rock with individual pieces ranging in size from 1 cm. to 15 cm. Digested sewage sludge from the Regional Municipality of Sudbury is mixed with the rock layer to fill the interstices. This sludge ,not only blocks the oxygen transfer to the tailings but also will be a partial source of nutrients for the ultimate vegetative cover. Another test made possible by the reasonable proximity of a source of a fine waste alkaline material,is the use of this material to block the rock interstices.

The second method consists of a 2 m. thick layer of domestic garbage from the Regional Municipality of Sudbury which is covered with a 30 cm to 60 cm (1-2 feet) stabilization layer. It is anticipated that the methane generated by the decomposition of the garbage will act to block the oxygen.

Various organic materials are being tested in developing wet covers on tailings as an oxygen barrier by Falconbridge (Griffiths, !988). The idea is to construct a swamp with water to act as the oxygen barrier along with the growth of swamp plants.

The preliminary results from the tests with both types of covers, wet and dry, indicate some improvement in the quality of the seepage water. However, more research in this area is needed.

The reclamation of uranium tailings in the Elliot Lake area poses many of the same , but also a few different, problems to thoise encountered in the more traditional tailings materials from sulphide ores. The extraction of uranium uses a sulphuric acid leaching system. The mil;ling of thore produces a material with no particle bigger than 0.5mm (0.02 in.). Following the extraction of the uranium, the resulting waste material (tailings) is discharged to the disposal area. Upon settling, the its texture ranges from a fine sand to a very fine silt. The principal mineral is quartz (85%) with smaller amounts of pyrite (2-5%), mica, thorium, radium 226, and calcium sulphate (5%).

The difference between laboratory determination of limestone requirement and the field experience graphically shows the diference in working under completely controlled conditions and in the field where control of the various factors impacting is minimal. In the laboratory, itwas found that applications of limestone above 22 tonnes/ha. (10 tons per acre) gave the optimum benefit when it was completely mixed through the tailings. On the other hand, under field conditions it was found necessary to apply up to 65 tonnes/ha.(30 tons/acre).

The major treatment of the tailings surface and revegetation at Rio Algom took place between 1971 and 1978. Current observations (1988) of the areas, some ten plus years later, provide some rather interesting information. Where maintenance fertilization was carried for at least 2 years, the vegetation developed into a viable stabilizing ground cover. In areas where fertilization was limited, the herbaceous ground cover is sparse. However, if this same surface is protected from water and wind erosion, native trees and shrubs have colonized the area. In areas of high fertilization, the competition from the grasses has not permitted this colonization. The areas susceptible to erosion soon returned to the barren state. This also has occurred in some slimes areas where a high acidic water table had restricted access and plant establishment. These observations illustrate how critical it is to get the vegetation established as soon as possible after the surface preparation and the neutralization of the area to be seeded.

As can be seen from the foregoing, the emphasis in the resarch area of tailings stabilization is switching to developing walk away scenarios when a tailings area is ready for abandonment from the revegetation alone. In the case of sulphide tailings, the acid generation potential must be handled to reduce the metal content of seepage waters. Vegetaive covers in their roll of precipitation interceptors, transpiration agents and as providers of organic matter for decomposition will continue to have a roll in the improvement of seepage water quality. Their proven rolls as surface stabilizers and aesthetic aids to the environment are now just part of the overall tailings stabilization scheme.

Regulations

Although specific regulations concerning tailings revegetation are often not spelt out in the various provincial acts and guidelines, nearly all are open to the interpretation that it can be required. This requirement is becoming more and more the practice.

The provincial requirements must be as strict as the federal ones and they can be stricter.

The requirements are subject to change and it is advisable that these be reviewed with the local coontrol personnel before a new project is commenced or a major alteration made to an existing operation.

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TABLE 1 METAL AND INDUSTRIAL MINERAL MINES/MILLS IN EASTERN CANADA

PROVINCE	MINERAL	COMMODITY	NUMBER OF (1) FACILITIES	1986 (2) PRODUCTION (x10)
Ontario	Metals:	Gold	18	46700 g
		Silver	3	437 KG*
		Base Metal	3	599400 Kg
		Nickel	16	137000 Kg
		Iron Ore	3	13200 T
		Uranium	4	4445 Kg
		Magnesium Calcium & Strontium	1	N/A
	Non Metals: (not including: lime, dolomite, calcium and cement)	Gypsum	3	1309 T
		Nepheline Syenite	2	485 T
		Talc	2	N/A
		Salt	5	6708 T
		Silica		832 T
Quebec	Metals:	Gold	18	29464 g*
		Silver	0	50 Kg*
		Iron Ore & Titanium	3	13200 T
		Columbium	1	N/A
		Base Metal	11	109045 Kg
	Non Metals: (not includung: lime, calcite, cement and chromite)	Asbestos	4	515 T
		Silica	4	821 T
		Talc	1	40 T
		Salt	1	N/A
		Graphite	1	N/A
New Brunswick				
	Metals:	Gold	1	107 g*
		Base Metal	1	249570 Kg
		Antimony	1	N/A
	Non Metals: (not including: lime, cement, calcium and dolomite)	Potash	2	191 T
		Silica	2	N/A
		Coal	1	600 T(est)
		Silica	2	N/A

* Includes by-product silver from gold and base metal mines.

** Includes by-product silver from gold and base metal mines.

TABLE 1 METAL AND INDUSTRIAL MINERAL MINES/MILLS IN EASTERN CANADA (Continued)

PROVINCE	MINERAL COMMODITY		NUMBER OF (1) FACILITIES	1986 PRODUCTION (x10)(2)
Nova Scotia	Metals:	Tin	1	N/A
		Gold	1	N/A
	Non Metals:	Gypsum	6	6164 T
	(not including:	Salt	2	N/A
	lime, cement,	Silica	1	N/A
	calcium and	Barite	1	1211 T
	dolomite)	Coal		2900 T (est)
Newfoundland	Metals:	Iron Ore	2	19465 T
		Base Metal	1	6686 Kg
	Non Metals:	Gypsum	3	449 T
	(not including:	Asbestos	1	45 T
	cement)	Pyrophilite	1	N/A
		Silica	1	N/A

Source: 1) Canada, Energy, Mines and Resources, 1987 (a)

2) Canada, Energy, Mines and Resources, 1987 (b)

TABLE 2 DISTRIBUTION OF TAILINGS IN EASTERN CANADA.*

Mine Type	Cu,Pb,Zn,Ni.			Au,Ag.			Fe.		
Province	Open	Closed	Veg	Open	Closed	Veg	Open	Closed	Veg
Newfoundland	57	45	0				460	0	0
Nova Scotia	0	39	26						
New Brunswick	307	24	18						
Quebec	1093	242	39	785	624	257	370	0	0
Ontario	1711	171	278	1175	1372	265	1033	12	3
Totals	3168	521	361	1960	1996	522	1863	12	3

	Uranium		
	Open	Closed	Veg
Newfoundland			
Nova Scotia			
New Brunswick			
Quebec			
Ontario	172	340	33
Totals	172	340	33

* Area in hectares.

Canada, Energy, Mines and Resources, 1975.

AREA OF PROVINCES

Newfoundland	37,163,735	hectares
Prince Edward Island	566,171	"
Nova Scotia	5,284,093	"
New Brunswick	7,156,913	"
Quebec	135,780,889	"
Ontario	91,743,326	"

OVERVIEW OF TAILINGS RECLAMATION IN WESTERN CANADA[1]

by

Paul F. Ziemkiewicz[2] and Ross Gallinger[3]

Abstract. Coal, oil sands, potash, precious and base metals are mined in western Canada. Each produces its characteristic type of tailings. Reclamation is controlled by local regulatory requirements and by the nature of the tailings and adjacent land uses. The tailings range from innocuous to highly reactive; posing short term revegetation concerns to indefinite maintenance problems. Major, unresolved technical problems occur with oil sand tailings and sulfide metal mine tailings.

Introduction

Mining in Western Canada was one of the region's earliest attractions for settlement and development. Coal, oil sand, precious and base metal deposits were discovered in the first explorations of the west which occurred in the mid to late 18th century.

Upon arrival of the railroads in the 1890's many attractive mineral deposits had been located and evaluated but not developed. Coincident with the Industrial Revolution, this encouraged development of large-scale integrated mining and processing operations. This was particularly true in the base metal and coal sectors while precious metal mining focussed on small, high grade deposits.

The 1960's brought a major upsurge in western Canadian mining with development of low grade copper deposits in British Columbia, potash mining in Saskatchewan, development of the Alberta oil sands and massive coal projects. While the early mining activity was subject to little environmental regulation, this later wave of activity brought the regulations under which the mining industry now operates. As a result of its history, most of the original, large mining and processing centers are still active. While there are many small, abandoned precious metal mines, few centers large enough to process ore and thus create tailings have been abandoned.

Location of Impoundments

Mining activities and their tailings impoundments are located throughout western Canada. Each province and territory, however, has a characteristic set of tailings types related to the regional geology and type of mining. Metal mining is associated with the Laurentian Shield which occurs in the eastern half of Manitoba, northern Saskatchewan, the Northwest and Yukon Territories.

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Metal mining also occurs throughout British Columbia.

Most of Western Canada's coal mining is restricted to the Cretaceous and Tertiary sedimentary basin of Saskatchewan, Alberta and British Columbia with scattered deposits on Vancouver Island and central British Columbia. All of Canada's surface mineable oil sand occurs in northeastern Alberta.

Origin and Range of Properties

There are four principal types of tailings impoundments in Western Canada. Metal mining produces both siliceous and sulfide tailings. The latter tend to occur with low grade ore deposits and thus individual impoundments are generally. Sulfide tailings occur with a variety of base and precious metal mines and like them tend to occur as small to medium sized operations. While the siliceous tailings are relatively inert, sulfide tailings are highly reactive.

Non-metal mining operations include potash, coal and oil sands. The processing of potash ore includes a solution phase which extracts NaCl and other impurities. The extract also includes significant amounts of KCl. The brines are stored in above ground tailings ponds. While most western Canadian coal is burned at mine mouth power plants, the higher grade export coals are washed prior to shipment. Western Canadian coal generally contains less than 1% sulfur and the overburden rock tends to be calcareous. The resulting tailings, like the coal, are low in sulfur and are non-reactive. In cases where the principal shale is smectitic, dewatering can be the major problem.

The oil sand mining operations of northeastern Alberta are unique in the world. They are among the largest earth moving operations on Earth. The ore contains from 6 to 12% bitumen and after processing the remainder becomes tailings, in addition to solids, process water is captured as slimes. The result is a post mining landscape which is nearly all tailings. The scale of the operations makes this a particular challenge as a mining operation may contain 60 square kilometers of tailings.

Problems

In Western Canada tailings are usually stored in one of the three following ways: in above-grade, diked ponds, within mined-out pits or in the ocean or large lakes. The above-grade pond offers the greatest potential for isolation of the tailings since foundation conditions can be selected to minimize percolation into groundwater and catchment systems can be installed to collect liquids which pass through or over the dike. However, this type of pond requires maintenance of the dike and the catchment system at least until the contents are dewatered. Evaporation in Western Canada is a slow process. In many cases closed basins accumulate rather than lose water.

In-pit storage is a useful means of disposing those liquid tailings which pose little threat to groundwater. Underwater tailings disposal is a controversial technique. This method was widely applied in the past along the fjords of the British Columbia coast and one active copper mine in British Columbia still employs underwater disposal. Concerns center on the effect of tailings on fisheries. A recent application to reopen a molybdenum mine near Prince Rupert, B.C. was rejected because the Government found underwater disposal of tailings unacceptable.

While there are many differences, all operations have a few problems which are common to all mines. Among the latter is the fact that most minesare located in areas of varying isolation. This makes regulations difficult to enforce in a consistent manner. There are common technical problems as well. For mine tailings these include the issues surrounding storage of often noxious liquids. Issues include tailings dam construction and maintenance and with these all of the attendant public safety, liability and environmental factors. This is a temporary concern where tailings dewatering occurs promptly but assumes major, long term importance in those cases where dewatering does not occur.

Most jurisdictions require that solid tailings surfaces be vegetated. This is a straightforward matter where the tailings are not toxic to plant growth. Many siliceous metal mine tailings, oil sand solid tailings and coal tailings usually require improvement in their nutrient and water storage capacities. Sulfide metal mine tailings and saline potash tailings require special treatment.

Regulations

In Canada the requirement to reclaim mine tailings is generally dealt with under the appropriate mining and reclamation regulations. Provincial governments have full jurisdiction over the regulatory process and the federal government is only involved to the extent required by its air and water pollution legislation. In the Yukon and Northwest Territories, however, the federal government plays the major regulatory role.

Federal

The Yukon and Northwest Territories comprise 99% of federal land in Canada. Reclamation requirements are generally imposed as conditions on mine leases. There are 25 different acts, regulations and special cabinet directives for policies setting out rules for mining development. Enforcement is tailored to the federal Fisheries Act and the Northern Inland Waters Act with the consequent focus on effluent discharge. Guidelines have been adopted which describe good practice in the design and operation of a mine to minimize water pollution.

Provincial

The four western provinces regulate tailings within the context of their provincial mine reclamation policy. Thus, application is made at the time of the mine permit to construct, operate and abandon tailings ponds in much the same manner as the other components of the surface disturbance. The provinces attempt with varying levels of success to coordinate this effort with other requirements respecting dam safety, water use and water impoundment. The drafting, adoption and enforcement of reclamation legislation is entirely within provincial jurisdiction.

Canadian federal and provincial laws are enabling rather than restrictive and contain such phrases as "the Company shall undertake reclamation to a standard satisfactory to the Minister". Legislation often empowers the minister to develop regulations concerning specific mining activities. Regulations stipulate more specific conditions than legislation and may refer to highly specific guidelines. However, like most Canadian law, reclamation legislation is permissive with respect to defining the minister's power. It avoids wording which restricts the minister's discretion. It is therefore difficult to characterize provincial requirements as the resulting system is, at its best, extremely flexible and adaptable.

Ecological Situation

In Western Canada mine tailings are generated in all of its five ecological zones: prairies, boreal forest, arctic tundra, mountains and the Pacific coast. The prairies are characterized by rich mollisolic soils and provide the land base for the Canadian small grain and livestock industries. This region of southern Manitoba, Saskatchewan and Alberta is a single sedimentary basin of Cretaceous to Tertiary age and is home to all the potash and much of Western Canada's coal industry. Since this coal is subbituminous to lignitic, however, it is not upgraded for export and there are no coal tailings on the prairies. The Saskatchewan potash mines are the principal source of tailings on the prairies. These underground mines occur in Aspen Parkland to Mixed Prairie vegetation types. The climate is continental with extremely cold winters and short, dry summers.

Much of the region's metal mining occurs in the Boreal Forest of northern Manitoba, Saskatchewan, the western part of the Northwest Territories and all of the Yukon. In addition, the region contains the Alberta Oil Sands. The Boreal Forest consists of subdued to flat topography and locally poor drainage. It covers the northern portion of the Interior Sedimentary Basin and the southern portion of the precambrian Laurentian Shield. Climate is cold, continental with extremely cold and long winters and short, dry summers.

The region north of the Boreal Forest is Arctic Tundra. It, by definition, has no tree cover and the vegetation consists of low shrubs, forbs and gramminoids. The geology is both Cretaceous/Tertiary sedimentary and Precambrian Laurentian Shield. Soils, where present, tend to be thin and organic. The climate is the coldest to be found on the continent and the region is subject to continuous darkness in midwinter. Permafrost is continuous.

Western Alberta, the Interior of British Columbia and the Yukon occur within the Western Cordillera. This region includes numerous mountain ranges separated by deep, glacially carved valleys. Geology includessedimentary through crystalline rock in variously disturbed condition.

Vegetation ranges from ponderosa pine/bluebunch wheatgrass in the drier areas to white spruce/englemann spruce/douglas fir forests over most of the slopes and subalpine fir to alpine tundra at the highest elevations. Soils are generally inceptisols though some mollisols, alfisols, spodosols and histosols occur. Discontinuous to continuous permafrost is present in the Yukon.

The eastern part of the Cordillera contains all of its present coal production. Since these mines produce washed metallurgical coal for export, tailings ponds are present at each of the mines. Numerous precious and base metal mines are located in the region including several large smelting and processing centers. Other land uses include forestry, grazing and recreation.

The British Columbia coast consists of a series of fjords and the steep, heavily forested slopes of the Coast Range. Flat land is scarce and siting of tailings ponds becomes a major problem. The region is subject to precipitation ranging from 225 to 750 cm per year. Most of this arrives as rain particularly at the lower elevations. The Coast is the center of the British Columbia forest industry with extremely productive forests. It also acts as the principal spawning ground for the western Canadian commercial fishery. The principal sources of tailings have historically been base and precious metal mines.

Reclamation

Manitoba

Location and Activity. Mining activity in Manitoba is focused principally onbase metals and to a lesser extent on the precious and non-metallic resources. Minerals produced include copper, lead, zinc, nickel, silver, gold, cadmium, cesium, tantalum, and gypsum. The base and precious metal resources are located in the boreal forest region ofnorth-central Manitoba. Production is largely underground with only a few surface operations. The deposits exist in mixed volcanic and sedimentary sequences and usually consist of sulfides. Mineralization includes pyrrhotite, pyrite, chalcopyrite and sphalerite.

Gypsum and tantalum resources are located in the southern portion of Manitoba in the Prairie and Plains regions. These small deposits occur in sedimentary structures and complex zoned pegmatites.

Practices and Constraints. The combined production of tailings in Manitoba exceeds three million tonnes per year, and they are created by conventional crushing, grinding, sizing and flotation techniques. The coarse fraction recovered from tailings is used as backfill in underground operations. The finer fraction and slimes are pumped to tailing ponds for storage.

Many Manitoba mines have made full use of the topography in the design of tailings disposal systems. One mine utilizes a series of lakes to store tailings effluent and maintain the plant water supply. The effluents are impounded in these lakes by small dams built of waste rock, glacial till and tailings sand. The runoff is monitored for any increases in particulates or soluble metal contaminants. Another mine pumped a lake dry to gain access to the ore body and subsequently utilized the site for tailings disposal.

The principal constituents of tailings in this province are iron sulfides and silicate minerals. At one minesite alone, an area of approximately 253 hectares have been covered by sulfide tailings. These tailings are a major source of airborne dust and react to form sulfuric acid.

Reclamation of acid generating tailings has proven to be a challenging task. Much research has been conducted toward a vegetation cover on sulfide tailings. Establishment of some agronomic grass species was encouraging when heavy lime additions were made to the tailings. However, this is not considered a permanent solution as the tailings continue to react and generate strongly acidic, metal-rich waters. Fresh tailings can have a pH of 6.5 to 7.5, but after weathering and oxidation, the pH is reduced to 2.5 to 4.0. Other growth limiting factors associated with sulfide tailings include harsh microclimate, nutrient deficiency, excessive soluble salts, hard pan formations, and mobilization of toxic metal ions.

Other alternatives for reclaiming these wastes are being investigated. These include flooding, water or organic emulsion sprays, snow fences, plowed furrows, and coverings of gravel, rock, top soil, muskeg or a combination of coverings.

Saskatchewan

Location and Activity. The two major minerals mined in Saskatchewan are potash and uranium. Limited base and precious metal production occurs in the north-central area. The potash of Saskatchewan is located in the south-central portion of the province. This deposit is of Middle Devonian Age and occurs in beds near the top of the Prairie Evaporite formation. The potash-bearing zone contains three predominant minerals: halite, sylvite, and carnallite. The estimated reserves of potash in Saskatchewan contain 118 billion tonnes of KCl.

Uranium mining is concentrated in the northern region, generating tailings of more than 1 million tonnes per year. The ore zone is in metamorphosed sediments and volcanics. Uranium mineralization occurs as pitchblende associated with hematite, chlorite, and carbonate, or is confined to a brecciation zone characterized by intensive chloritic alteration.

Practices and Constraints. Potash is mined and crushed underground. The broken rock is crushed, scrubbed with brine solution then treated by floatation to separate potash from halite. The potash product is dried, sized and packaged for shipment.

The resulting tailings consist mainly of halite with some clay impurities. The tailings are pumped to large storage ponds. Small quantities of common salt and road salt are recovered from these ponds by evaporative techniques. Large quantities of halite tailings are produced at each mine, since approximately 1.5 tonnes of halite are produced for each tonne of K20 equivalent.

An alternative to conventional underground potash mining is solution mining. Boreholes are drilled through the potash beds and a hot solution is injected under pressure. The holes are washed while brine solution is withdrawn from the bottom. Processing consists of evaporation, crystallization and halite separation. A portion of the waste halite is used to produce high-purity product by vacuum-pan evaporation.

Research is being conducted on reclaiming the large saline tailings ponds, especially since they occupy land in the middle of agricultural areas. Some work is aimed at disposing saline waste as backfill in abandoned underground workings.

Saskatchewan is the largest producer of uranium in Canada, with an annual production of 7,722 tonnes per year. One of the largest uranium mills in the world is located at Key Lake, Saskatchewan. Ore extraction is accomplished by both underground and open pit methods. The milling process at the Key Lake operation involves crushing and grinding. The process creates a thickened pulp which is subjected to a two stage leaching circuit. The ore is leached with sulfuric acid under oxidizing conditions. From the leaching circuit, the process stream enters a series of countercurrent decantation thickeners yielding the uranium bearing solution and tailings. Uranium is precipitated with ammonia to produce yellowcake, which is dried and prepared for packaging.

All tailings and liquid wastes are treated in a bulk neutralization plant. All effluents are treated to pH 11 to prevent sulfuric acid formation by residual sulfides. The high amount of lime required to raise the pH results in the formation of gypsum, making the tailings nearly impermeable to seepage. In addition to lime neutralization, barium chloride is added to tailings slurry to fix radium as a radium-barium sulfate complex.

Tailings impoundments are constructed with an impervious underseal consisting of a bottom layer of sand covered with a blanket of till and bentonite.

Sub-aerial deposition is utilized to achieve tailings densities of 35 to 40 percent solids at pH 11. Layers are deposited in approximately 10 cm thicknesses and with four to five layers established. Upon abandonment, tailings are covered with clay seals and revegetated with agronomic grass and legume mixtures.

Alberta

Location and Activity. Two types of mining activity generate tailings in Alberta: oil sands and export coal.

Oil sand developments are operated by Syncrude Canada Ltd and Suncor Inc. (formerly Great Canadian Oil Sands Ltd.-GCOS). These are integrated operations consisting of mining, bitumen extraction and upgrading. The product of both plants is synthetic crude oil. The Syncrude facility produces 20,000 cubic meters of synthetic crude oil per day and Suncor produces 11,000 cubic meters per day. These plants are located on the only surface mineable oil sand deposits in Canada: the Athabasca oil sands. These deposits are located in the northeastern corner of Alberta about 500 km northeast of Edmonton. The surface mineable oil sands are estimated to contain 3.5 billion cubic meters of recoverable crude bitumen.

Alberta produces about 22 million tonnes of coal per year. About one half of this amount is either high grade thermal coal or metallurgical coal. Both types of coal deposit are located on the eastern boundary of the Rocky Mountains. The thermal coal deposits are of Cretaceous to Tertiary age and are often associated with bentonitic interbedding. The metallurgical coals are of Jurassic to early Cretaceous age, occur in thick (up to 15 meters) seams and are associated with durable shales and sandstones. There are three active metallurgical coal mines and two export thermal mines in Alberta. Four of these are near Hinton, Alberta and one is near Grande Cache, Alberta.

Practices and Constraints. Both Syncrude and Suncor utilize the Clark Hot Water Process for extracting bitumen from its sand matrix. The process separates the bitumen and leaves a slurry consisting of 50% water and a solid fraction of sand, silt and clay. As a result of incompletely understood hydration phenomena among the clay fraction (largely illite), soluble organic molecules and possibly metal ions, a stable sludge develops which defies consolidation beyond about 30% solids. This results in a vast net loss of process recycle water in each cycle along with a commensurate storage problem. The total net volume of the tailings (sand plus sludge) is 40% greater in volume than mined ore.

At the end of its 25 year life a typical oil sand plant producing 20,000 cubic meters per day of synthetic crude oil will require a 22 to 31 square kilometer tailings pond.The liquid contents of the pond will consist of about 400 million cubic meters of sludge. The sludge will remain in a liquid state indefinitely and will be impounded behind dikes built of tailings sand. Dike heights will reach from 55 to 100 meters above ground level. The tailings dike must support the interior tailings sludge until it consolidates and develops sufficient strength that it can support itself without external support. With present methods of oil sand tailings pond development it will probably be thousands of years before the fines stabilize. The liquid portion of the tailings has a pH of 8.3 and contains an undefined suite of organic compounds.

Protection of surrounding waters is important since the pond leachate has been found to be acutely toxic to rainbow trout. The toxicity of the tailings liquid in the natural environment has not been evaluated. As a result of the uncertainty which this causes, the Alberta Government requires that all liquids be stored on site and that no discharge be permitted. The regulatory approvals also require that at the end of the operations no liquid tailings remain on site. Since closed basins in this region accumulate water, evaporation is not expected to solve this apparent dilemma.

Coal washing follows conventional technology in that the coal is crushed, washed and separated into fine and coarse streams. The coal is separated from the associated shale through a heavy medium process. The tailings consist of coal particles, coal shale mixtures, free shale and clay particles. There have been no reports of these tailings becoming reactive. Even after several decades of exposure to air the pH remains neutral in these tailings. Nor have any plant toxins been identified in significant concentrations. The tailings have excellent moisture holding properties though the surface is often dry. The primary constraint to reclamation is that the tailings are black and have good insulating properties. As a result, they become hot enough on sunny summer days to kill young seedlings. This problem diminishes as the vegetation cover is established or if the surface is covered by spoil or soil. These tailings are also very susceptible to wind erosion. Since summer weather in this region tends to be hot, dry and windy cover crop establishment requires excellent timing.

The metallurgical coal mines have few dewatering problems since the associated shale is reasonably durable. The tailings dewater rapidly and form a firm surface. One mining and coal cleaning operation in Alberta, Smoky River Coal Ltd. feeds its coal tailings into a power plant operated by Alberta Power Ltd. As a result of this arrangement only a small, short term tailings pond is required and the tailings stream is reduced to coal ash. The dry ash is then stored in diked structures and covered with overburden and soil. The ash was evaluated for toxicities and none were found.

Tailings associated with the export thermal coal mines frequently contain significant amounts of smectite. The smectite is a 2:1 expanding lattice montmorillonitic clay whose cation exchange complex is dominated by sodium. It has a vast potential to adsorb water, often doubling its mass with absorbed water. In the cretaceous and tertiary coal seams of the Alberta plains and foothills, smectite occurs as interbeds within the coal seams and as a constituent of the overburden. These clay bands disperse during washing and contaminate the circuit with clay particles. Fine coal losses can be high as a consequence. Despite the smectite content of the tailings, however, dewatering is rapid and the tailings form a solid surface soon after the free water is decanted to the mine's drainage water settling ponds. Since the tailings volume is large, the regulatory agencies work with the companies to arrange acceptable storage schemes. These often include mined out pits.

The Alberta legislation requires that all coal tailings be covered with either suitable overburden or soil to usually 1 to 1.5 meters in depth. This facilitates revegetation of the surface and eliminates the dust problem usually associated with coal tailings in western Canada.

The chemistry of coal tailings effluents have been studied in a number of proprietary reports. While the tailings water chemistry has not generated significant concern, there have been concerns over some of the flocculent which are added to settling ponds in order to lower suspended sediment levels. Indeed, suspended sediment seems to be the primary risk associated with coal tailings water.

British Columbia

Location and Activity. In British Columbia, a variety of base and precious metals are mined, including copper, lead, zinc, molybdenum, iron, gold and silver. Many mines are located in the south, although there are several in the central and western regions of the province.

There are five large operating coal mines in British Columbia which produce a total of about 15 million tonnes of cleaned coal per year. All of these mines exploit metallurgical coal seams though some of the production consists of thermal coal. Three of the mines are located in the extreme southeastern corner of the Province, near Sparwood, B.C. The other two are in the northeastern part of the Province near Dawson Creek.

Practices and Constraints. Tailings resulting from the British Columbia coal mines are nearly identical to those found in the Alberta metallurgical coal mines. Unpublished data indicates that in coal samples taken from a modern tailings pond near Sparwood, B.C. five years after it had been closed and vegetated, pH was found to average 7.7 with little variation. Samples of the same tailings pond were reported by the British Columbia Department of Agriculture to have a pH of 7.5. Coarse tailings from 19th century underground mining operations nearby had pH's ranging from 6.6 to 8.1, averaging 7.2. Coal sample analyses by the British Columbia Department of Agriculture indicated, as well, an average pH of 7.2. There is little documentation on the chemical properties of western Canadian coal tailings simply because revegetation has yet to encounter any chemical limitations. The characterizations thus far have been undertaken to verify the observations of field workers that these tailings are chemically innocuous, even after many years of exposure to air.

Unlike Alberta, the British Columbia government does not require that tailings be covered with either mine spoil or soil. Revegetation thus commences directly on the tailings. This tends to make cover crop establishment more difficult. Until the cover crop is established, wind blown dust remains a problem and, where near residences, a source of ongoing complaints. The coal tailings contain an average of about 40 to 50% coal. Various schemes to burn coal tailings for power generation have been advanced in British Columbia though none have been undertaken.

Base and precious metals are mined by both open pit and underground methods. Mineral extraction and tailings generation are accomplished by conventional crushing, grinding and floatation of ore deposits. Some past and present mines have utilized marine disposal of tailings. Abandoned mines at Tasu and Britannia Beach, B.C., discharged tailings into the Pacific Ocean. One operating mine near Port Hardy, B.C., deposits copper tailings into Rupert Inlet with some impacts upon the marine environment. Underwater tailings disposal in lakes has become a controversial technique due to past operations impacting upon water quality.

Most mining operations deposit tailings in constructed containment structures and utilize the supernatant in the milling process. The chemical nature of tailings in British Columbia is diverse ranging from acidic sulfide tailings to neutral siliceous tailings. Considerable attention is being focused on the generation of acid mine drainage (AMD) caused by the oxidation of sulfide tailings and waste rock. Expensive containment and treatment facilities have been constructed at three minesites to protect the environment from AMD discharges.

Reclamation efforts have concentrated on short term solutions, while long term abandonment techniques are researched. Current acid tailings reclamation includes the wet option whereby tailings are stored underwater by flooding the impoundment. Covering techniques involving impermeable seals and soil media have faced problems of upward migration of AMD and salts. Research has discovered that an interface layer of coarse rock between the acid tailings and the cover material is required to reduce upward migration problems. Sub-aerial deposition of tailings by spigots or spray bars has been promoted to increase the density of tailings, lower permeability and to create a structurally stable impoundment. These deposition techniques can help to restrict upward migration and reduce the volume required for storage.

In general, nitrogen and phosphorus are low in tailings materials and become major growth limiting factors. In acidic tailings toxic amounts of metal ions can inhibit plant growth. Large additions of fertilizer assist the establishment of agronomic species on tailings. The use of red fescue and white clover with 300 to 600 kg/ha of high phosphate fertilizer is a common practice for establishing vegetation on tailings in British Columbia. Uptake of copper and molybdenum by plants grown on these tailings may be potentially toxic to domestic and wildlife species.

Yukon and Northwest Territories

Location and Activity. During the past decade, base metals and uranium were the major mining activity for the Yukon and Northwest Territories. Large lead-zinc mines have been the major sources of tailings generation but precious metal resources will become significant contributors in the future. Most mining operations in both the Yukon and Northwest Territories tend to be extremely remote, with limited overland access. The deposits are usually high grade sulfide ores and may contain galena, sphalerite, pyrrhotite, chalcopyrite, marcasite, magnetite, arsenopyrite, pyrite, and tetrahedrite.

Practices and Constraints. There is very little information available on tailings reclamation in the far north. The bulk of information on arctic reclamation is related to oil exploration seismic lines, service roads, drill sites, and pipelines.

Many tailings ponds are sulfidic and, upon oxidation generate acidity. Also, high concentrations of soluble salts can occur with acid or alkaline tailings. These properties, combined with the extremely cold, dry climate limit the plant species available for revegetation. Best results have been achieved by setting the stage for natural succession by native vegetation. At an abandoned mine northwest of Yellowknife, N.W.T. several stages of natural plant succession had occurred since closure, but large areas were still barren. Areas with organic matter consisting of stumps, brush, ash, old mine debris, and animal wastes provided suitable habitats for native species establishment.

A mine near Faro, Yukon, has tailings with a sulfur content of 30 to 40% (by weight). No species have been able to survive on these tailings. The proposed abandonment plan for the impoundment entails raising the dam to permit flooding. A spillway would be constructed to maintain the water at a specific level. The cost of this plan is estimated at C$50 million.

DESIGN AND RECLAMATION OF MINE WASTE FACILITIES TO CONTROL ACID MINE DRAINAGE[1]

by

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and

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Abstract. The economics of mine waste management are often greatly influenced by the potential of the waste to generate acid mine drainage (AMD). If mining operations result in the exposure of sulphide bearing rock which has the capacity to produce AMD, control measures are necessary to protect the environment. This is particularly important in the long term, after mining operations have ceased. Facilities such as tailings deposits, waste rock dumps and open pits in acid generating rock need to be designed to prevent AMD damaging the environment. Existing facilities need to be reclaimed such that AMD is reduced to insignificant levels. If AMD is not controlled, there is potential for considerable harm to the immediate aquatic environment.

A number of mines in British Columbia are either producing or have the potential to produce AMD. Considerable effort is being directed towards developing effective, economic control measures in this Province. This paper describes the currently available AMD control measures. Important lessons may be learned from sites where AMD is occurring and from those sites where reclamation plans, that are designed to control AMD, have been implemented. A recommended approach to the design and implementation of control measures is presented.

Introduction

Acid mine drainage (AMD) may be defined as contaminated drainage that occurs as a result of natural oxidation of sulphide minerals contained in rock which is exposed to air and water. Mining in sulphide bearing rock is one activity which may lead to the generation and release of AMD, although not all operations that expose sulphide bearing rock will necessarily result in AMD. Acidic drainage will not occur if the sulphide minerals are non-reactive, nor if the rock contains sufficient base potential to neutralize the acid, nor if appropriate control measures are successfully implemented.

In British Columbia (B.C.), AMD was first observed in 1928 at the Britannia Mine (Errington and Ferguson, 1987) where mining began in 1905, however the date of initial release of AMD is not known. Acid mine drainage has had some major detrimental affects on B.C.'s environment. Errington and Ferguson report that five abandoned mines are affecting streams. At one mine site (Mt. Washington) they reported that AMD has contributed soluble metal loadings to a salmon river (the Tsolum) at a sufficient level to be partly responsible for the loss of fisheries resources in the river for 11 kilometres. Until recently, the potential for a new mine to generate AMD was often not adequately anticipated during the planning stages; due mainly to a lack of understanding of the problem. Some operating mines, such as Equity Silver, have had to institute very costly treatment measures to prevent severe damage to the environment (Wilkes, 1987).

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AMD currently experienced from mining activities in B.C. and the Yukon occurs predominantly from waste rock facilities at hard rock metal mines. While AMD does occur from underground workings and tailings deposits, open pits and waste rock dumps are the major AMD sources. On the other hand, in Eastern Canada, AMD from tailings is of major concern particularly at the underground uranium, copper and nickel mines in Ontario and Quebec. This trend is probably due to a number of factors. In B.C. metal mining in sulphide ores tends to be open pit mining with resultant large quantities of waste rock. The waste rock, while not necessarily high sulphur content, has very low buffering capacity and is durable and hence permeable, allowing acid generation to occur and be realized rapidly. In Eastern Canada, underground mining is more predominant with lesser quantities of waste rock, and the waste rock that is produced tends to have a greater neutralization potential. AMD develops more rapidly from waste rock than tailings deposits. Thus the AMD from the relatively "young" B.C. and Yukon tailings deposits may not have developed to their maximum potential.

Available Control Measures

An approach to the prevention and abatement of AMD is described by Robertson and Barton-Bridges (1988). This approach applies control of AMD in three categories, or levels of control, as follows:

1) Control of acid generation.

2) Control of AMD migration.

3) Collection and treatment of AMD.

The control of AMD by preventing or inhibiting acid generation is the most preferable level of control. If acid generation is prevented there is no risk of the resultant contaminants entering the environment. The formation of acid at the source may be prevented by excluding one or more of the essential ingredients or by controlling the environment around the sulphides. The essential ingredients in the acid generation process are; reactive sulphide minerals, oxygen and water. Criteria that influence acid generation, in terms of rate of production, include oxygen and water availability, nature of sulphides, bacterial activity, temperature, and pH.

The next level of control is to prevent or reduce the migration of AMD to the environment. Since water is the transport medium for contaminants, the control technology relies on the prevention of water entry to the AMD source. Control of water exit is of little value since in the long term all water entering the AMD source must exit, long term storage being negligible.

The third level of control, after control of acid generation and AMD migration, is to collect and treat contaminated drainage. The collection and treatment of AMD has been the most widely applied abatement measure to date. Treatment measures can be either active systems which require continuous operation, such as a chemical treatment plant, or passive systems which are intended to function without intervention by man, such as wetlands. Chemical treatment involves technology which is well established and is working effectively at a number of mines.

A number of control measures are available in each of the categories listed above. The suitability of individual measures depends on many factors including; site specific conditions, the length of time during which the control is to remain effective, and whether the control is for an existing or proposed waste facility. The currently available control measures in each of the three categories are listed in Table 1. These measures include both short and long term controls and each method will likely experience a different level of success, depending on the project and site specific conditions. The most effective control might be achieved by incorporating a combination of measures from each of the three categories of control. The methods listed in Table 1 will not be described in detail here, other than to mention the most effective long-term control measures and to discuss the geotechnical considerations in the design of soil covers, and the diversion or collection of surface and ground water.

Long-Term Control Methods

There are at present three control measures that have the potential to be successful in the long term depending on the application and site criteria. These measures are; water covers,

TABLE 1

Available AMD Control Measures

Control of Acid Generation

- Conditioning of tailings or waste rock to remove or exclude sulphide minerals.
- Covers and seals to exclude water.
- Covers and seals to exclude oxygen (including water cover).
- Waste segregation and blending to control pH.
- Base additives to control pH.
- Bactericides to control bacterial oxidation of sulphide minerals.

Control of AMD Migration

- Covers and seals to exclude infiltration of precipitation.
- Controlled placement of waste to minimize infiltration.
- Diversion of surface water.
- Interception of ground water.

Collection and Treatment of AMD

Surface and groundwater collection systems together with treatment as follows:

- Active systems, e.g. chemical treatment plant.
- Passive systems, e.g. treatment by wetlands.

soil covers, and collection and treatment of AMD. Each of these measures have clear advantages and disadvantages in terms of both effectiveness and cost.

The most secure long-term control measure currently available is to provide a water cover over the reactive waste. This generally serves to exclude oxygen to such an extent that the rate of acid generation is reduced to negligible levels. Water cover may be implemented by placing the waste directly under water, by flooding the waste after placement and maintaining flooded conditions, or by means of saturated soil or bog covers. If designed correctly, this measure may offer protection with minimal long-term maintenance. Water cover is often only feasible for new mines due to the high costs of either re-handling existing waste or tailings deposits in order to place these under water, or of constructing structures to maintain flooded conditions in the long term. In the case of existing tailings deposits, it may be practical and feasible to maintain saturated conditions if the tailings are contained behind water retaining structures. An example of water cover to control AMD in B.C. is the Island Copper Mine on Vancouver Island where waste rock and tailings are placed under water in Rupert Inlet (Steffen Robertson and Kirsten, 1988).

Soil covers show promise as inhibitors of oxygen (particularly to coarse rock waste dumps) and, probably more importantly, as barriers to infiltration. The effectiveness of soil covers as oxygen barriers is influenced by the moisture content maintained in the cover. A cover that can be maintained in a saturated condition will be more effective, primarily due to the low solubility and diffusivity of oxygen in water and due to prevention of desiccation cracking. Soil covers have been used to abate AMD from existing wastes where water cover is not feasible. An example of the application of a soil cover to rock waste in B.C. is the abandoned Mount Washington mine on Vancouver Island (Healey and Robertson, 1989). The effectiveness of such covers is still to be determined by long term field testing, as is currently being done at a number of sites (NTDME, 1986; Steffen Robertson & Kirsten, 1986b; Healey and Robertson 1989). The geotechnical considerations in the design of soil covers are discussed in more detail below.

At some existing facilities, the only practical option available to control AMD is to collect and treat the contaminated drainage. Collection is only possible if surface and groundwater flows can be intercepted and stored to allow appropriate treatment. This is an exercise in geotechnics and geohydrology. The main disadvantage of chemical treatment is that it requires continuous operation and maintenance. There is a relatively high risk of equipment or power failure which makes back-up or contingency measures necessary, and a need to dispose of large volumes of sludge. Chemical treatment, while it offers a secure short-term method of achieving environmental protection, may not offer a cost effective long-term solution.

Geotechnical Considerations in the Design of Soil Covers

Simple Soil Covers

In the interest of minimizing cost; a simple, single layer, soil cover is preferred. A fine textured soil, such as clay or silt, is required to limit infiltration. To effectively limit oxygen transport it is necessary to maintain the layer at a high moisture content. A single soil layer, however, is limited in its effectiveness for the following reasons.

- Without capillary barriers, a simple soil cover is prone to large seasonal variations in moisture content. This could result in desiccation cracking and hence an increase in permeability. In addition, decreasing the moisture content of the soil increases the rate of oxygen diffusion. These seasonal variations are greatest near the surface and are therefore greatest for thin covers. For single layer soil covers to be effective they need to be relatively thick to maintain a saturated zone during the dry season. The cover thickness required is probably a function of the climate but is likely to be of the order of 2 m for regions such as B.C.

- The fine-grained soils required to limit infiltration may be frost susceptible. Ice segregation may result in degradation of the cover and increased permeability. Frost heave may also make the surface of the cover irregular, allowing ponding and increased infiltration. Permeability changes may also result from root action and biotic activity.

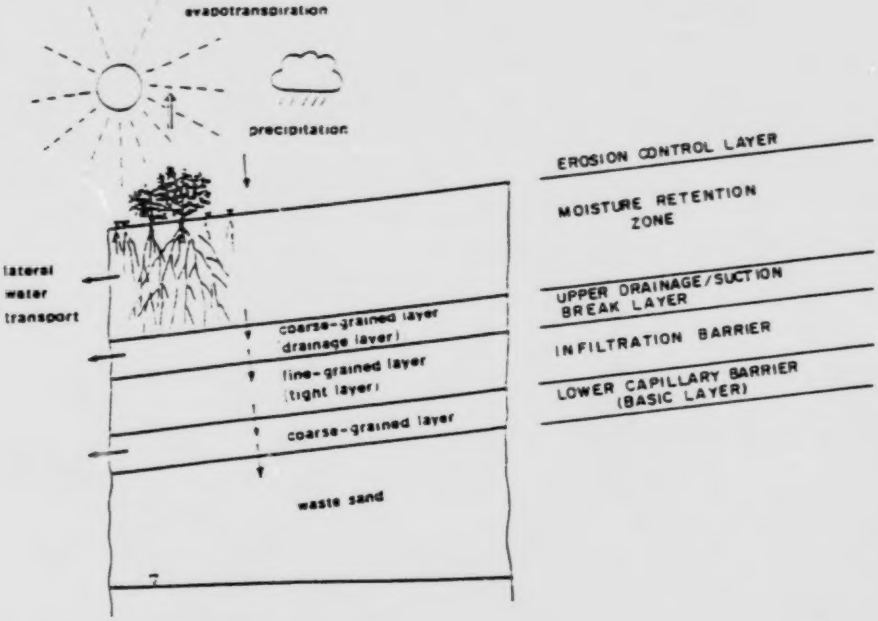
- A simple soil cover does not have the ability to prevent moisture being sucked up from underlying tailings (or vice-versa) by capillary action. In net evaporation regions, it does not limit the migration of salts from the tailings to the surface due to surface evaporation and transpiration.

- A simple, single layer fine-grained soil cover may not be able to adequately withstand wind and water erosion or burrowing and root action. Some form of erosion protection, such as vegetation or rip-rap is normally required.

These limitations on the effectiveness of a single soil layer can be overcome by using complex covers, as described in the next section.

Complex Soil Covers

The effectiveness of soil cover is greatly improved by adopting a complex cover design consisting of several layers, each performing specific functions to improve water and oxygen exclusion and long-term stability. These layers and their specific functions are described below. A typical complex cover design is illustrated in Figure 1 (Rasmuson and Eriksson, 1987).


evapotranspiration
precipitation
lateral
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coarse-grained layer
(drainage layer)
fine-grained layer
(tight layer)
coarse-grained layer
waste sand
EROSION CONTROL LAYER
MOISTURE RETENTION
ZONE
UPPER DRAINAGE/SUCTION
BREAK LAYER
INFILTRATION BARRIER
LOWER CAPILLARY BARRIER
(BASIC LAYER)

Figure 1 Concept for a Soil Cover for Reactive Tailings (after Rasmusson and Eriksson, 1987)

Erosion Control Layer. Erosion protection can be provided by vegetation or by a layer of coarse gravel or rip-rap. The establishment of vegetation on the waste dumps is desirable for aesthetic and land use reasons. Therefore, revegetation is usually the most desirable method of providing erosion control. However, where revegetation is not practical or will not sufficiently control erosion coarse gravel or rip-rip may be required.

Studies for uranium tailings deposits in Canada (Steffen, Robertson and Kirsten, 1986a) indicated that forest cover would adequately control sheet and rill erosion, and wind erosion, but methods of analysis are not available to assess the effectiveness of vegetation to control gully erosion. A vegetation cover design guide has been prepared for U.S. uranium tailings deposits by Beedlow (1984). While this design guide illustrates and discusses many of the aspects relevant to vegetation cover design, it is not necessarily directly applicable to B.C. mine waste deposits. A similar guide for the design or rip-rap erosion protection has been prepared by Walters (1982).

A special study on vegetative covers was recently carried out as part of the Uranium Mill Tailings Remedial Action Project (UMTRAP) in the United States (U.S. Department of Energy, 1988). This study investigated the use of vegetation to stabilize uranium tailings, and specifically includes the use of vegetation to intercept infiltration. The principal finding of the study is that properly developed plant communities on complex soil covers can be effective in stabilizing covers and controlling infiltration on top slopes of waste piles. The study showed that the appropriate vegetative cover will adapt to climatic change, will repair itself after severe disturbances such as fires and droughts and will persist indefinitely with little or no maintenance. The plants were found to protect topslopes against sheetwash erosion, however, resistance to gully erosion depends more on the overall pile configuration rather than on the vegetation and soil.

Certain physical, chemical and vegetative stabilization methods have been evaluated for purposes of mine waste reclamation by the U.S. Bureau of Mines (Dean, et al, 1986). This study incorporated field testing of these different methods and costs for the various stabilization procedures.

Moisture Retention Zone. The purpose of the moisture retention zone is to provide a zone for moisture retention to limit desiccation of underlying layers. It also provides a growth medium to support vegetation. Moisture retention is therefore desirable for two reasons:

i) It helps to keep the infiltration/oxygen barrier moist. This helps prevent desiccation cracking and reduces oxygen diffusion.

ii) By retaining moisture after a precipitation event it supports vegetation and allows time for evapotranspiration to occur, thus reducing infiltration.

The soil used to construct the moisture retention zone would generally be a loam soil with a substantial sand fraction.

Upper Drainage/Suction Break Layer. The upper drainage/suction break layer serves two primary purposes:

i) To drain water laterally from the surface of the infiltration barrier, preventing ponding.

ii) To prevent moisture loss from the infiltration barrier due to upward capillary suction.

Prevention of ponding reduces infiltration. Keeping the infiltration barrier moist helps to reduce oxygen diffusion and prevents desiccation cracking. This layer can also be designed to prevent intrusion by burrowing animals if it incorporates large gravel. For drainage to be effective it must be constructed with a cross fall of 1% or greater.

The effectiveness of this layer would be expected to decrease with time as it becomes clogged with roots and organic debris and fines, and as the drainage slope is modified by long-term settlement of the underlying tailings or rock waste.

Infiltration Barrier. This is a low-permeability layer consisting of fine-grained soil or synthetic materials (or a combination of both). Its purpose is to prevent the downward infiltration of moisture and the diffusion of oxygen into the waste. The lower the permeability of this material, the more effective it is as a barrier to infiltration. The objective of this layer is to provide a sufficient barrier to enable the overlying coarse-grained layer to drain infiltration.

Lower Capillary Barrier. Rasmusson and Eriksson (1987) investigated the use of capillary barriers, beneath the infiltration barrier, to reduce infiltration. The principle is that, if negative pore-water pressure is maintained in the low permeability material at the interface with the underlying coarse grained capillary barrier, infiltration into the lower layer would be prevented. They found that this would only be effective if ponding on the low-permeability layer does not occur, which would be difficult to achieve in practice. However, for soil covers over fine grained waste deposits such as tailings, a capillary barrier beneath the infiltration barrier may be useful in preventing suction of contaminated pore water from tailings up into the cover in dry periods.

The long-term performance of a complex soil cover could be greatly reduced if fine-grained materials are allowed to migrate into the coarse-grained layers. Filter layers should be considered.

Basic Layer. A basic layer could be incorporated into the design to reduce the pH of infiltrating water and therefore acid generation rates. Alkaline materials such as lime or limestone could be spread over the surface of the waste, before placing the cover, or mixed into the cover layers.

Limestone is commonly mixed with waste rock during placement at coal mines with great success and research is being done on the addition of phosphate rock (Chiado et al, 1988). It is also proposed for short-term acid generation control in the waste rock at the Cinola project (Robertson and Barton-Bridges, 1988). The potential for acid generation control by surface applications of alkaline materials is less attractive than mixing them with the waste. Limestone has a low solubility in near neutral water, and the resulting alkaline charge is therefore small and may be insufficient to control AMD. Surface inflows tend to be concentrated at isolated locations such as depressions, cracks, permeable zones, etc. At these locations the available alkaline materials are quickly exhausted. The addition of a basic layer would not significantly reduce acid mine drainage where unsaturated conditions predominate, such as in waste piles. It would be more beneficial in saturated tailings, and might be usefully employed in tailings impoundment covers.

Effectivenss of Soil Covers

Information on the relative effectiveness of soil covers in controlling acid mine drainage may be obtained from the results of mathematical model simulations of covers, and from the results of monitoring of actual covers. Figure 2, developed from results using the RATAP model (Senes and Beak, 1986) illustrates the effect of depth of a till cover on typical tailings from the Elliot Lake project for various depths of unsaturated tailings (Steffen Robertson and Kirsten et al, 1987).

Figure 3 shows the effects of various types of covers on infiltration rates as predicted by the HELP model for acid generating tailings at Elliot Lake (Steffen Robertson and Kirsten et al, 1987). The results show considerable benefit of a complex cover design over simple covers, and the benefit of adding a synthetic liner.

The results of the modelling indicate a range of infiltration (shown as "seepage" on Figure 3) from approximately 38% to 0.1% of precipitation, depending on the cover design. It is worth noting that single layer cover of rip-rap or high permeability soil serve to increase infiltration due to reduced runoff.

Evaluation and Design of AMD Control Measures

A step-by-step approach to the design and implementation of AMD control at either existing or proposed facilities is demonstrated by means of a flow-chart as shown in Figure 4.

The type of waste is an important initial consideration, due to the differences in physical properties of wastes and differences in suitability of the various control measures. The flow-chart first evaluates methods for controlling acid generation at the source, then considers AMD migration control measures, if required, and finally includes collection and treatment.

The development of a plan to control AMD should begin by evaluating the potential availability and feasibility of water cover, given that this is currently the most secure form of control. If underwater disposal is not possible or feasible, the remaining acid generation control measures should be evaluated. If one or a combination of the alternative measures can be shown to achieve the required control, there is no need to proceed further. The evaluation of the effectiveness of the control measures should be made with input from laboratory geochemical test results and possibly field tests, together with information from case histories.

If further control is required, methods to prevent or minimize the flow of water into the waste should be considered next. If this evaluation indicates that these measures, together with acid generation control, provide adequate control, no further measures are required. If the required control is still not achieved, collection and treatment of some form is required. The most cost efficient control may be provided by a combination of a number of methods from one or

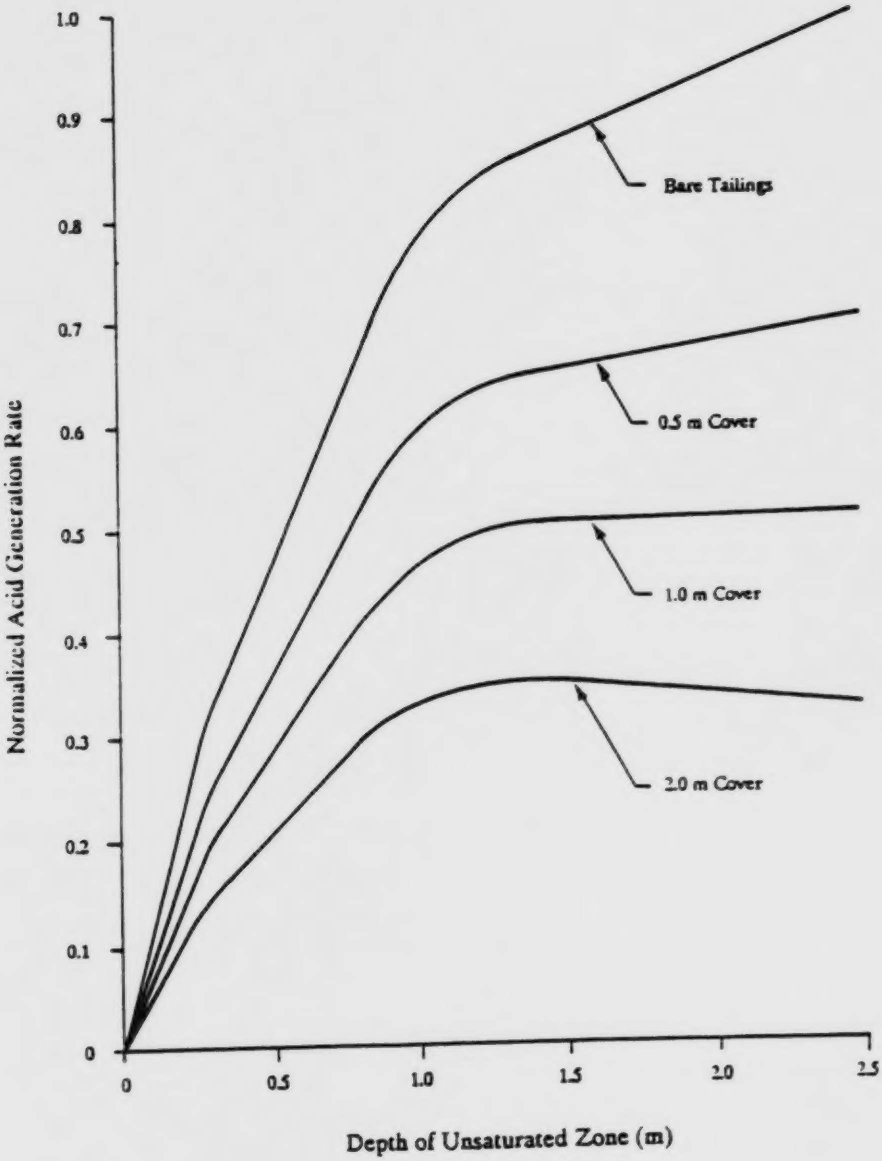
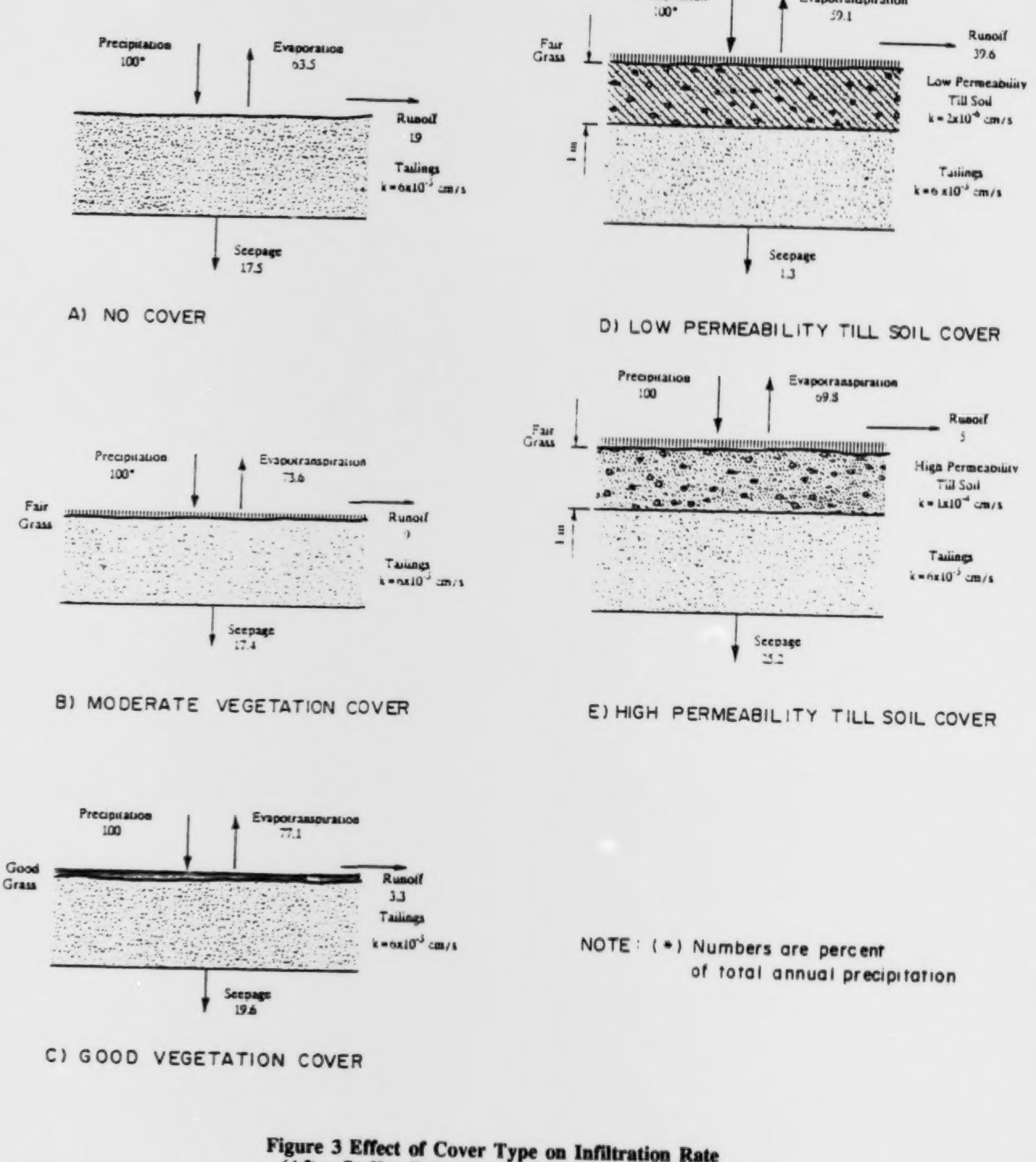


Figure 2 Effect of Till Cover Depth on Acid Generation Rate in Tailings (After Steffen Robertson & Kirsten et al, 1987)


Precipitation
100*
Evaporation
63.5
Runoff
19
Tailings
k=6x10^-5 cm/s
Seepage
17.5
Precipitation
100*
Evapotranspiration
59.1
Fair Grass
Runoff
39.6
Low Permeability
Till Soil
k=2x10^-6 cm/s
1 m
Tailings
k=6x10^-5 cm/s
Seepage
1.3
Precipitation
100
Evapotranspiration
69.8
Fair Grass
Runoff
5
High Permeability
Till Soil
k=1x10^-4 cm/s
1 m
Tailings
k=6x10^-5 cm/s
Seepage
25.2
Precipitation
100*
Evapotranspiration
73.6
Fair Grass
Runoff
9
Tailings
k=6x10^-5 cm/s
Seepage
17.4
Precipitation
100
Evapotranspiration
77.1
Good Grass
Runoff
3.3
Tailings
k=6x10^-5 cm/s
Seepage
19.6

A) NO COVER

D) LOW PERMEABILITY TILL SOIL COVER

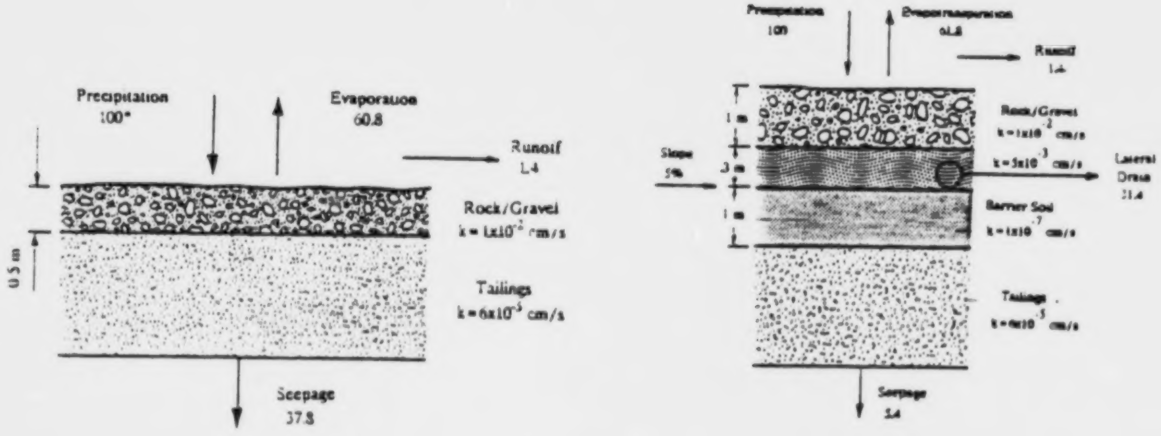
B) MODERATE VEGETATION COVER

E) HIGH PERMEABILITY TILL SOIL COVER

C) GOOD VEGETATION COVER

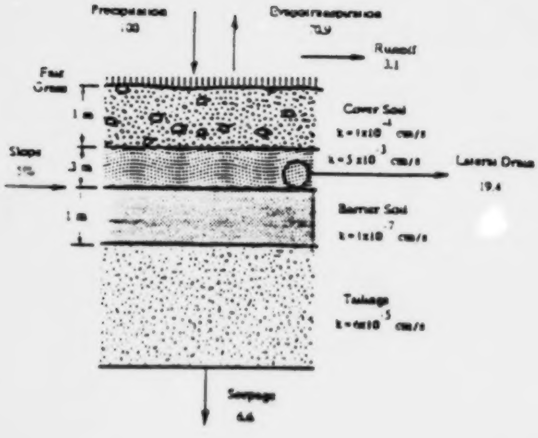
NOTE: (*) Numbers are percent of total annual precipitation

Figure 3 Effect of Cover Type on Infiltration Rate (After Steffen Robertson & Kirsten et al, 1987)

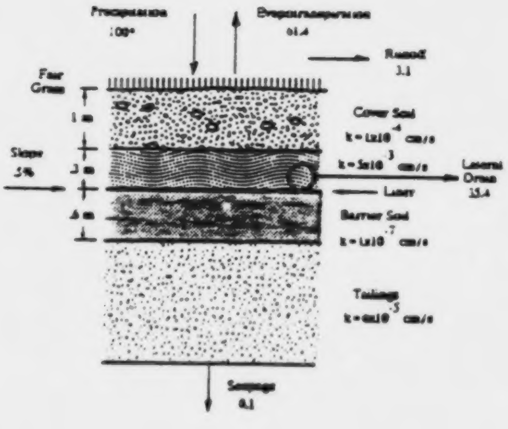

Precipitation
100*
Evaporation
60.8
Runoff
1.4
0.5 m
Rock/Gravel
$k = 1x10^{-2}$ cm/s
Tailings
$k = 6x10^{-5}$ cm/s
Seepage
37.8
Precipitation
100
Evapotranspiration
61.8
Runoff
1.4
1 m
Slope
5%
.3 m
1 m
Rock/Gravel
$k = 1x10^{-2}$ cm/s
$k = 5x10^{-3}$ cm/s
Lateral
Drain
31.4
Barrier Soil
$k = 1x10^{-7}$ cm/s
Tailings
$k = 6x10^{-5}$ cm/s
Seepage
5.4

F) RIPRAP EROSION RESISTANT COVER

H) SOIL BARRIER WITH LATERAL DRAIN AND RIPRAP COVER


Precipitation
100
Evapotranspiration
70.9
Runoff
3.1
Fair
Grass
1 m
Slope
5%
.3 m
1 m
Cover Soil
$k = 1x10^{-4}$ cm/s
$k = 5x10^{-3}$ cm/s
Lateral Drain
19.4
Barrier Soil
$k = 1x10^{-7}$ cm/s
Tailings
$k = 6x10^{-5}$ cm/s
Seepage
6.6

G) SOIL BARRIER WITH LATERAL DRAIN AND SOIL COVER


Precipitation
100*
Evapotranspiration
61.4
Runoff
3.1
Fair
Grass
1 m
Slope
5%
.3 m
.6 m
Cover Soil
$k = 1x10^{-4}$ cm/s
$k = 5x10^{-3}$ cm/s
Lateral
Drain
35.4
Liner
Barrier Soil
$k = 1x10^{-7}$ cm/s
Tailings
$k = 6x10^{-5}$ cm/s
Seepage
0.1

I) SOIL BARRIER WITH SYNTHETIC MEMBRANE LINER, LATERAL DRAIN AND SOIL COVER

Figure 3 (Cont'd) Effect of Cover Type on Infiltration Rate (After Steffen Robertson & Kirsten et al, 1987)

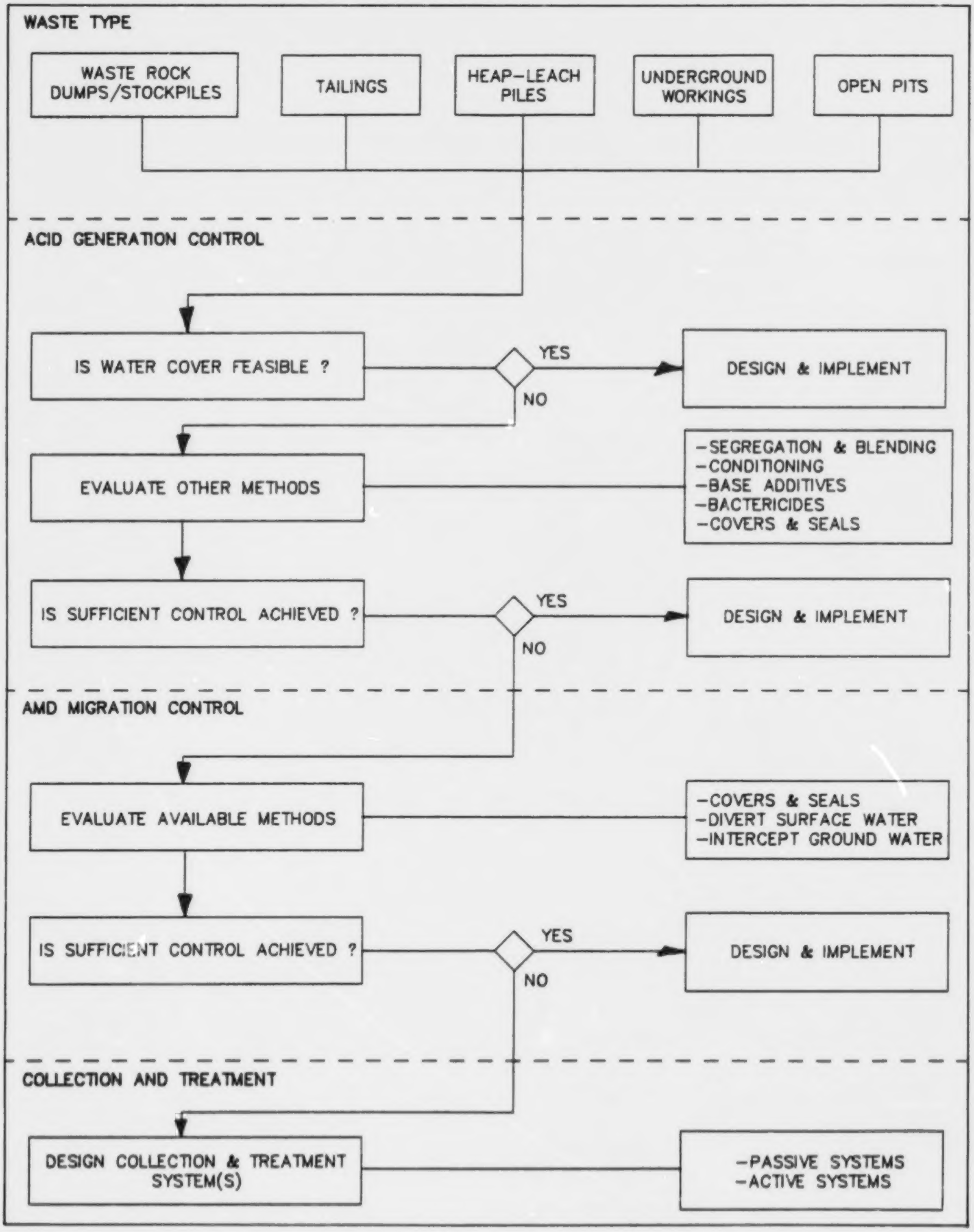

WASTE TYPE
WASTE ROCK DUMPS/STOCKPILES
TAILINGS
HEAP-LEACH PILES
UNDERGROUND WORKINGS
OPEN PITS
ACID GENERATION CONTROL
IS WATER COVER FEASIBLE ?
YES
NO
DESIGN & IMPLEMENT
EVALUATE OTHER METHODS
-SEGREGATION & BLENDING
-CONDITIONING
-BASE ADDITIVES
-BACTERICIDES
-COVERS & SEALS
IS SUFFICIENT CONTROL ACHIEVED ?
YES
NO
DESIGN & IMPLEMENT
AMD MIGRATION CONTROL
EVALUATE AVAILABLE METHODS
-COVERS & SEALS
-DIVERT SURFACE WATER
-INTERCEPT GROUND WATER
IS SUFFICIENT CONTROL ACHIEVED ?
YES
NO
DESIGN & IMPLEMENT
COLLECTION AND TREATMENT
DESIGN COLLECTION & TREATMENT SYSTEM(S)
-PASSIVE SYSTEMS
-ACTIVE SYSTEMS

Figure 4 Flow Chart Showing Approach to A.M.D. Control

all of the control categories. The cost of the control measure(s) arrived at by working through the flowchart must be compared to the cost of collection and treatment on its own to check that the most cost effective solution has been chosen.

Summary And Conclusions

Mining activity in sulphide bearing rock may produce waste that has the potential to generate acid mine drainage. If AMD is not controlled it poses a serious long-term threat to the environment due to the toxicity of dissolved heavy metals and other contaminants to aquatic life.

The impact of AMD may be minimized by controlling the acid generation reactions, by preventing the contaminants from entering the environment, or by collecting and treating the contaminated drainage. A number of control measures are available, some of which are better suited to short-term than to long-term control, and some measures are better suited to particular types of mine waste.

The most secure long-term control measure currently available is to provide a water cover over the reactive waste in order to exclude oxygen. The most obvious form of water cover is underwater disposal in natural water bodies or man-made impoundments. Disadvantages of this method include other potential environmental impacts associated with placing mine wastes in natural waters, and the high cost of its application to existing waste facilities.

Soil covers can be effective in inhibiting oxygen access to wastes, hence retarding the acid generation reactions, and as barriers to infiltration, hence controlling migration of contaminants to the environment. Current technology does not enable an accurate prediction to be made of the reduced rates of AMD resulting from covers and field scale tests are being performed at a number of locations, internationally. The effectiveness of soil covers as oxygen barriers is influenced by the moisture content maintained in the cover. The effectiveness of soil covers as barriers to infiltration depends on the ability of the cover; to resist erosion, to provide lateral drainage for run-off, to prevent moisture loss and resulting desiccation cracking, and to provide a low-permeability barrier to infiltration. Covers designed with multiple soil layers are more effective in meeting these objectives than single soil layers.

If the acid-generation reactions and the migration of contaminants to the environment are not controlled, the only remaining control is to collect and treat the AMD. This is, at some existing facilities, the only available option.

The evaluation and design of AMD control should be approached in a step-by-step manner, first evaluating acid generation control measures then proceeding to AMD migration control and finally collection and treatment.

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A CASE HISTORY OF AN ACID GENERATION ABATEMENT PROGRAM FOR AN ABANDONED COPPER MINE[1]

by

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and

Dr. A. MacG. Robertson, P. Eng.[3]

Abstract. This paper discusses a program that was initiated to improve the water quality of receiving waters below an abandoned copper mine on Vancouver Island in British Columbia. The poor quality of the water is the result of Acid Mine Drainage (AMD) from an open pit and associated waste dumps at the minesite. The program was further developed to determine the effectiveness of till covers as an abatement measure.

The first phase of the abatement program, which was commenced in August 1988, consisted of the consolidation of the waste rock, the placement of a glacial till cover and the installation of diversion ditches and drains. Surface application of limestone was also used to control pH levels in the creek during construction activities and as a short-term seepage treatment measure.

Instrumentation installed at the site includes gas/temperature wells, lysimeters and continuous flow recording devices. The monitoring program is ongoing and further activities at the site are planned for the 1989 construction season.

Introduction

For some sulphide-bearing rocks, the processes of chemical and bacterial oxidation of sulphides in the presence of water results in the production of low-pH water which dissolves metals contained in the host rock. Dissolved metals, such as zinc or copper, are then transported to downstream receiving waters. This is the phenomenon which is known as Acid Mine Drainage (AMD).

AMD has become the topic of considerable concern in British Columbia over the past decade. It is reported that there are 5 operating and at least 6 abandoned mines in British Columbia which produce acid drainage. Concern regarding the impact of AMD has developed over this period also in other parts of Canada and elsewhere in the world where AMD is experienced. As a result, considerable research is being applied to the problem.

AMD from an open pit and waste dumps at an abandoned Mount Washington mine on Vancouver Island, B.C., was identified in 1986 (Kangasniemi and Erickson) as a major contributor of contaminant loading, particularly copper, in the Tsolum River. Total copper concentrations, at certain times of the year, were found to be toxic to salmonid. Decreases in fish returns to the Headquarter Creek hatchery and the declining steelhead fishery were attributed to the AMD.

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[3] Dr. Andrew MacG. Robertson is the President of Steffen Robertson and Kirsten (B.C.) Inc., Vancouver, B.C.

In 1987 Steffen Robertson and Kirsten (SRK) completed a study for the Mount Washington minesite which evaluated several alternative AMD abatement options. Based on the findings of the study, an AMD abatement program for the Mount Washington minesite was commissioned by the B.C. Ministry of Energy Mines & Petroleum Resources (MEMPR) in May 1988. The objective of the program was to improve the water quality of the Tsolum River and to determine the effectiveness of till covers as an abatement measure.

Site Description and History

The Mount Washington mine site is located on the eastern side of the Insular Mountain Range at the headwaters of the Tsolum and Oyster Rivers. The site is about 1.5 km north of the Mount Washington ski resort and 25 km northwest from Courtenay, British Columbia. The site is accessible from the road serving the Mount Washington ski resort, but snow conditions preclude ground access during seven months of the year. A general location of the minesite, in relation to local access and drainage systems, is presented on Figure 1.

The minesite occurs at the northern end of the physiographic feature known as Forbidden Plateau. The local high ground is Mount Washington at an altitude of 1,590 m. A northwesterly trending ridge extends from the peak to the vicinity of the minesite. Across the minesite, which is located on the crest of the ridge, the ground surface varies from 1375 m to about 1320 m. The eastern and western flanks of the ridge are steep-sided, and drop away from the crest at slopes of up to 22 degrees. To the north, the front of the ridge drops in a series of steps.

Around the ridge, each flank drains to a different stream watershed. The northern and eastern flanks are the catchments for streams ultimately discharging to the Tsolum River. The western flank of the ridge drains to Piggott Creek, a tributary of the Oyster River. Figure 2 shows a more detailed layout of the minesite, and the drainage basins.

The bedrock underlying the site consists of marine extruded volcanics of the Karmutsen Group, marine sedimentary units of the Comox Group, and dioritic plugs and sills related to Tertiary intrusions. The surface has been sculpted by alpine glaciation, and, accordingly, the surficial deposits consist of morainal deposits and soils derived by insitu weathering. Soil development is sparse.

The minesite consists of two blocks: a southern block containing the main open pit with a waste dump along the southern perimeter, and a northern block containing a shallower open pit with two major waste dumps in addition to several smaller piles of waste rock. The south pit is estimated to be 24 metres in depth and covers an area of about 2 ha. Drainage from this pit and the dumps does not appear to contribute significant AMD and this area was not included in the abatement study.

The North Pit and waste dumps cover an area of about 7.4 ha. Locally, pit excavation reaches a depth of up to 10 m, but, in general, excavation is less than 5 m deep. The pit covers an area of about 4.4 ha at the southern end of the block, while the two major waste dumps - the East and West Dumps - had been developed over 3 ha around the northern perimeter of the block. Within the pit area, several small piles of waste rock were left. From north to south across the north pit and waste dumps, the ground surface drops about 60 m.

Activity in the vicinity of the mine dates back to the 1930's when initial exploratory work was undertaken. Mining commenced in 1964 and ended in November 1966. Ore was processed through a 750 tpd mill between 1965 and March 1967, and the associated mining produced 1.03 million tons of waste rock and overburden.

Waste Characterization

The bedrock is relatively homogeneous consisting primarily of felsic volcanics which, in places, is heavily weathered and extensively oxidized. The sulphide minerals occurring in the rock comprise pyrite, chalcopyrite, pyrrhotite and arsenopyrite. The waste material in the piles consists mainly of a pit-run material obtained by blasting and excavation of the adjacent bedrock, varying in size from 10 mm to 40 mm. In places, however, large boulders up to 1 metre in diameter were uncovered.

The chemistry of the seeps along the toe of waste dumps provided reasonable evidence of the presence of acid generating materials at the minesite. Seep surveys, completed prior to commencement of the abatement program, registered average pH values of 3.3; sulphate levels in the order of 400 mg/l; and copper concentrations of 17 mg/l. Acid base accounting tests completed on rock samples collected from within the pit areas indicated that the net neutralization potential of the waste material varied from -5 up to -290 kg of calcium carbonate

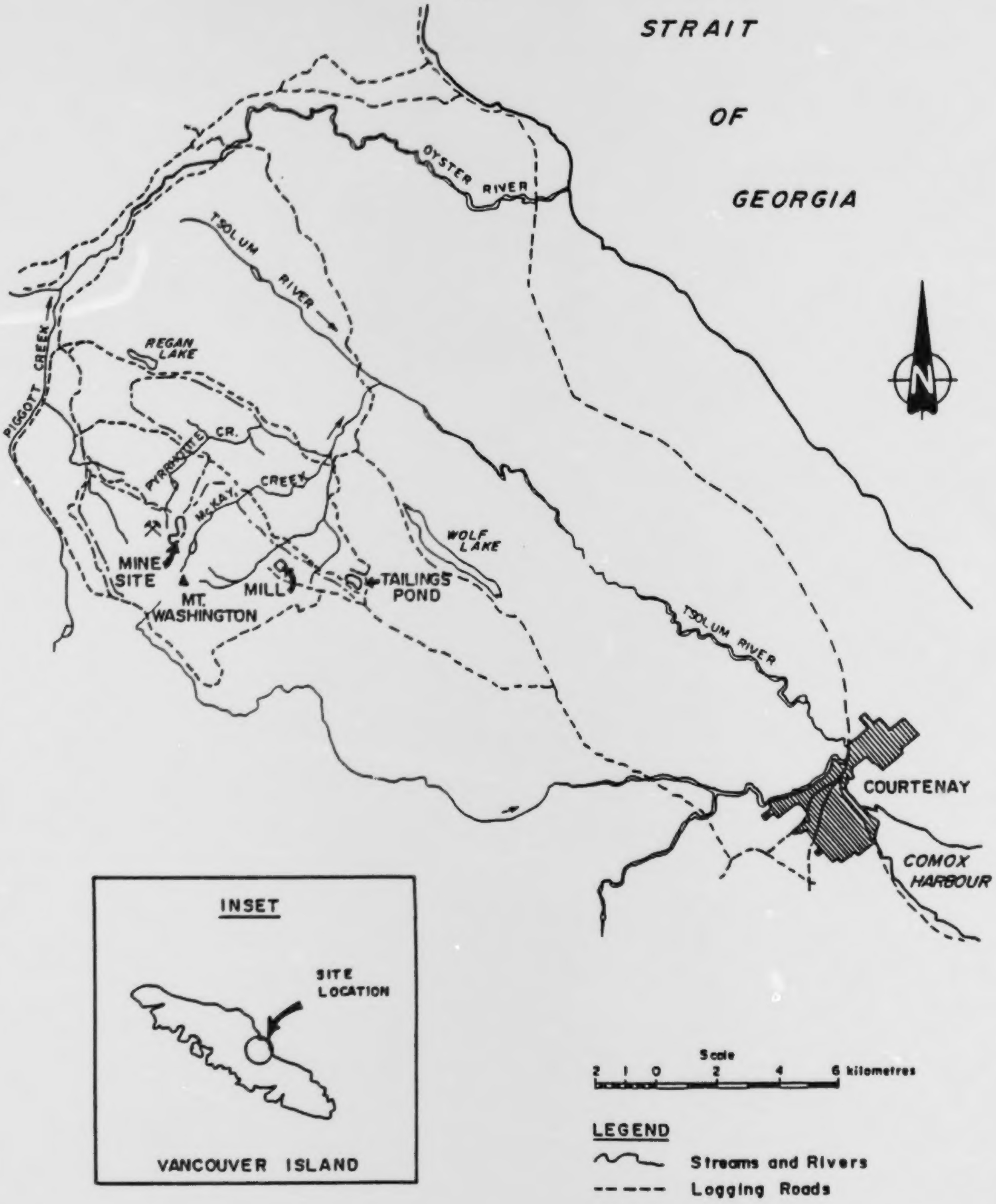
STRAIT OF GEORGIA
OYSTER RIVER
TSOLUM RIVER
PIGGOTT CREEK
REGAN LAKE
PYRRHOTITE CR.
McKAY CREEK
WOLF LAKE
MINE SITE
MT. WASHINGTON
MILL
TAILINGS POND
TSOLUM RIVER
COURTENAY
COMOX HARBOUR
N
INSET
SITE LOCATION
VANCOUVER ISLAND
Scale
2 1 0 2 4 6 kilometres
LEGEND
Streams and Rivers
Logging Roads
Local Access

Figure 1. Vicinity Map

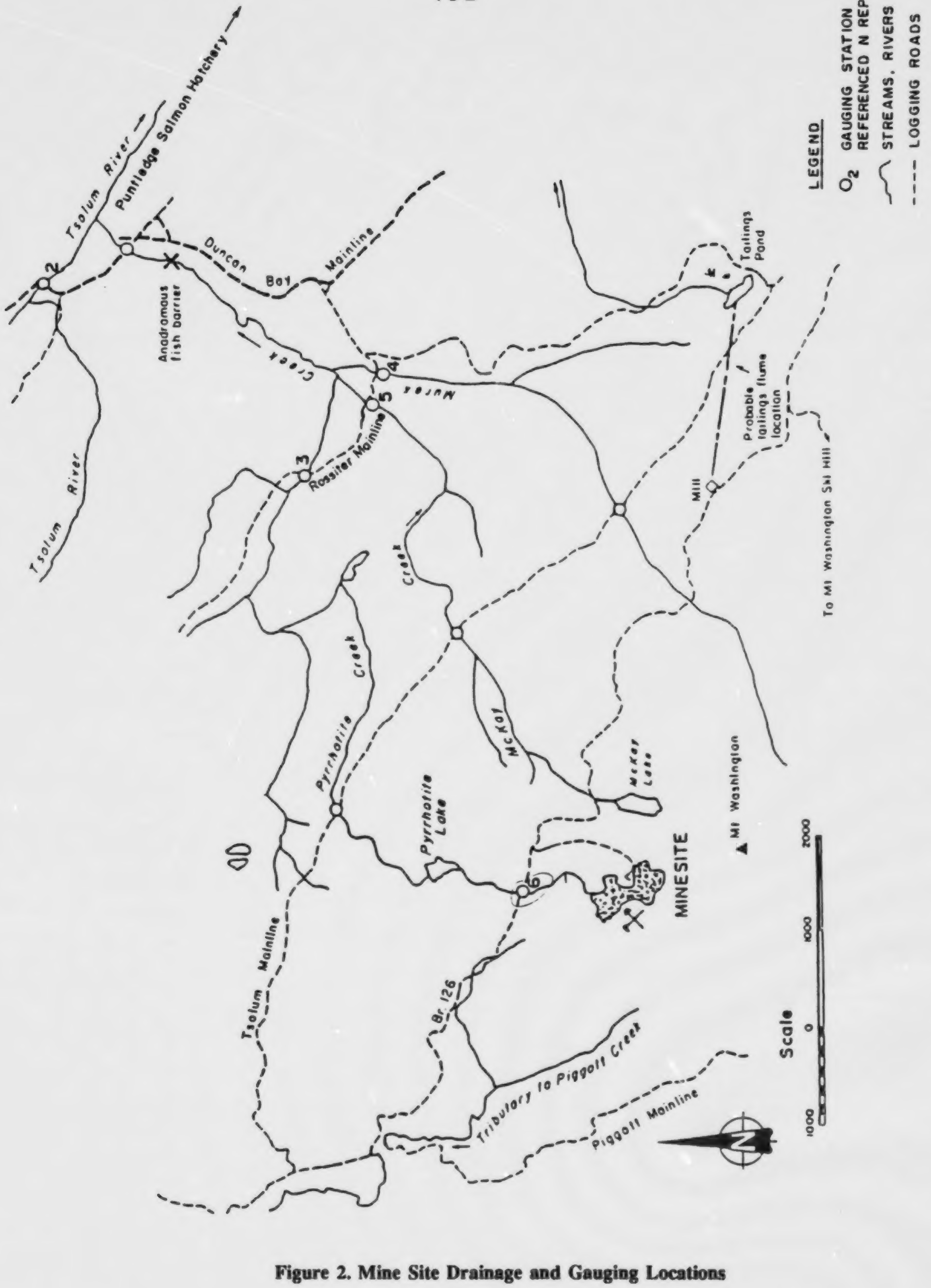
Tsolum River
Puntledge Salmon Hatchery
Duncan Bay Mainline
Anadromous fish barrier
Murex Creek
Rossiter Mainline
Tsolum River
Creek
Pyrrhotite Creek
McKay
McKay Lake
Pyrrhotite Lake
MINE SITE
Mt Washington
Mill
Probable tailings flume location
Tailings Pond
To Mt Washington Ski Hill
Tsolum Mainline
Br. 126
Tributary to Piggott Creek
Piggott Mainline
2
3
4
5
6
N
Scale
1000
0
1000
2000
LEGEND
○2 GAUGING STATION REFERENCED N REPORT
STREAMS, RIVERS
LOGGING ROADS

Figure 2. Mine Site Drainage and Gauging Locations

equivalent per tonne of sample. These results indicated that on average the waste rock had a relatively high potential for acid generation.

Acid Drainage

The contaminant transportation mechanism at the study area is a combination of seepage and surface runoff from snowmelt and precipitation. The drainage system appears to involve local recharge of perched flow paths in both the pit and the dumps, well above the deeper regional groundwater (estimated at greater than 30 m). The total contaminant loading at the toe of the dumps is generated from infiltration leaching of the stockpiled waste material and from the seeps in the pit area. Water quality analyses of the seeps in the pit area indicates the discharge is acid and high in metal content before it enters the waste material in the dump.

Acid drainage from the dumps and the pit area are within the Pyrrhotite Creek catchment and contribute a significant contaminant load to the creek. The Pyrrhotite Creek chemistry indicates low pH, high copper and moderate sulphate levels. A plot of the copper levels in Pyrrhotite Creek at a recording station 1 kilometre below the minesite, is presented on Figure 3.

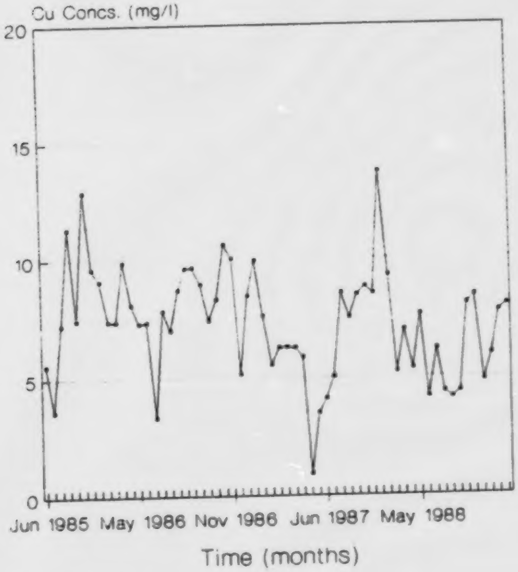

Figure 3. Copper Levels in Pyrrhotite Cr

Abatement Plan

Chemical oxidation requires the presence of reactive sulphide, water and oxygen. Biological oxidation can considerably increase the rate of acid production under favourable conditions. Thiobacillus ferrooxidans is the most important of a number of bacteria species which promote acid generation. This species of bacteria requires oxygen and is not effective in anaerobic conditions or where oxygen is precluded. Biological oxidation increases considerably once the pH drops below about 3.5.

It follows that acid generation can be controlled or reduced by:

- removal of sulphide
- exclusion or limitation of water
- exclusion or limitation of oxygen
- exclusion of bacterial activity.

The method selected for the control of AMD at the Mount Washington minesite was the construction of a low permeability compacted till cover over the waste material. The objective of the cover was to reduce access of water and oxygen to the waste material. Although the cover would not exclude water and oxygen to the extent that acid generation could not occur, the migration of AMD would be significantly reduced.

The plan involved collecting mine waste from the existing stockpiles and from the pit floor and consolidating the material into one dump. A 1-metre cover of compacted till would then be placed over the consolidated waste and an internal interceptor drain would be installed along the toe of the dump to control internal discharge. The collected seepage would be directed into a till-lined sump and discharged to Pyrrhotite Creek via a neutralization channel containing limestone. A till-lined diversion ditch would be constructed below the pit area to intercept seepage and runoff before it entered the dump.

The program also required the installation of gas monitoring wells within the dump and continuous flow recording devices and lysimeters.

Design Aspects

The till cover was designed as two 500 mm thick layers. The lower layer would be compacted to 95 percent of the Modified Proctor maximum dry density and would function as a low permeability barrier to infiltration. The upper or cover layer would have a relatively high permeability and would be compacted to 90 percent of the Modified Proctor maximum dry density. The cover layer would allow sufficient moisture to reach the barrier layer, preventing cracking of the barrier layer.

Estimates of the surface runoff, subsurface drainage and infiltration for the till cover were developed using the Hydrologic Evaluation of Landfill Performance (HELP) program developed by E.P.A. The model accepts climatological, soil and design data and accounts for the effects of surface storage, runoff, infiltration, percolation, evapotranspiration, soil moisture storage, and lateral drainage. A typical profile of the till cover and dump used in the model is shown on Figure 4.

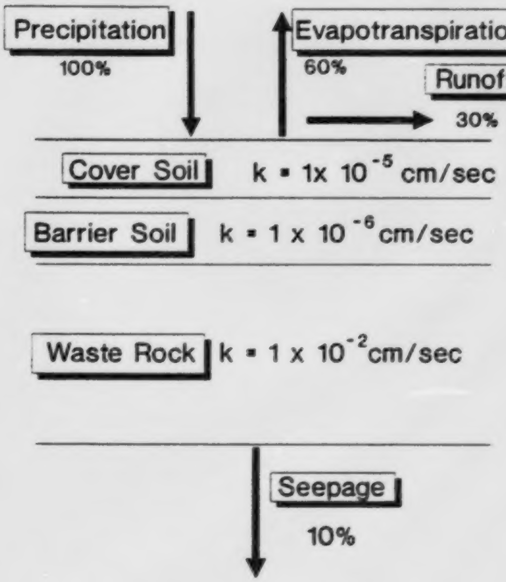

Figure 4. Typical Section for Infiltration Barrier

The design configuration for the dump required downstream slopes of 3:1 (horizontal to vertical). Compaction of the till covers on slopes steeper than this was considered impractical. The backslope of the dump was designed with a gradient of 5 percent to provide reasonable drainage without causing erosion. A typical section through the dump is shown on Figure 5.

The original design called for a central diversion ditch to intercept seepage and runoff from the pit area and surface drainage from the backslope of the dump. The design required the ditch to extend 500 mm into the bedrock with the invert and north flank of the ditch sealed with a gunite liner. Test pits excavated during construction, however, indicated that the depth of minewaste in the pit area was deeper than originally believed. Observations of the seep patterns within the pit during both wet and dry periods indicated that the seepage flows over the bedrock surface and then disappears back into the highly porous mine waste or fractured insitu bedrock. In an attempt to intercept the seepage, the ditch was realigned to follow the bedrock contour, as shown on Figure 6. The ditch was also downgraded to a temporary till-lined diversion ditch which would be replaced during the 1989 construction season with a permanent impervious channel.

The toe interceptor drain was designed to collect seepage from the dump and concentrate the flow to a sump located at the toe of the dump., The sump located within the dump would be sealed with glacial till and backfilled with drain rock. The outlet would be a 150 mm plastic overflow pipe. The sump was designed to allow discharge through the pipe while inhibiting air or oxygen entry. A typical section through the sump and overflow pipe is shown on Figure 7.

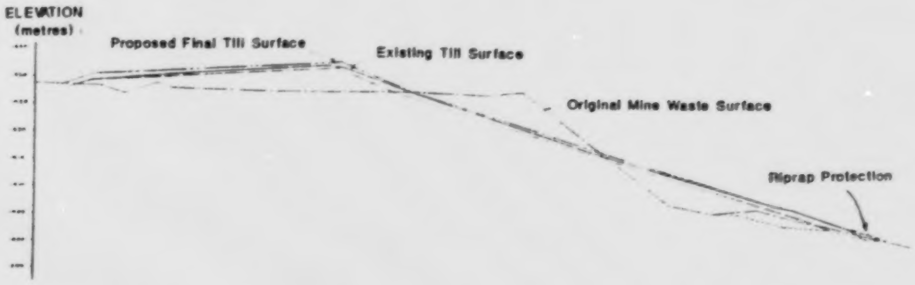

Figure 5. Typical Section Through Dump

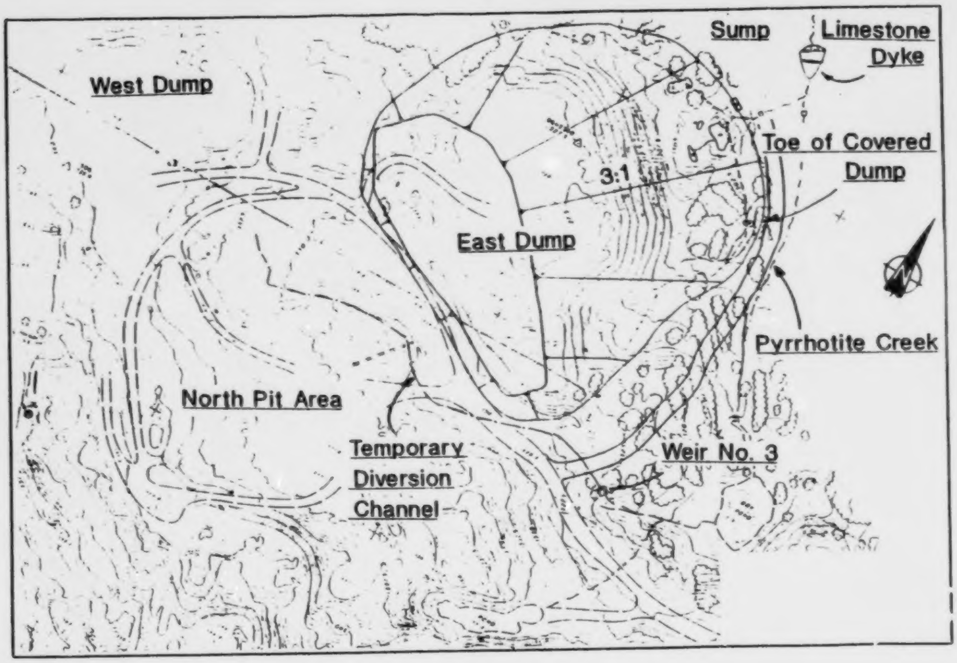
West Dump
Sump
Limestone Dyke
Toe of Covered Dump
3:1
East Dump
Pyrrhotite Creek
North Pit Area
Temporary Diversion Channel
Weir No. 3

Figure 6. Site Plan East Dump and North Pit

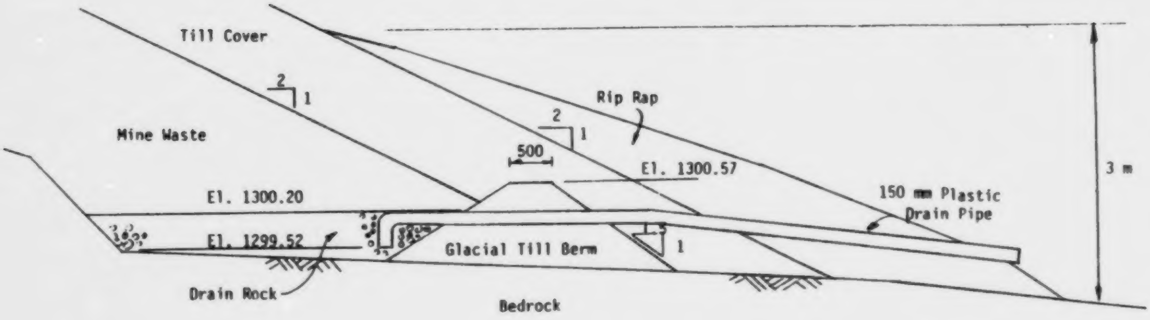
Till Cover
2
1
Mine Waste
Rip Rap
2
1
500
El. 1300.57
El. 1300.20
150 mm Plastic Drain Pipe
3 m
El. 1299.52
Glacial Till Berm
1.5
1
Drain Rock
Bedrock

Figure 7. Sump Detail

Construction Activities

Construction of Phase 1 of the minesite reclamation was completed between July and October 1988. During this period, the following major elements were constructed:

- Construction of 176 m of toe seepage collection ditch, sump and neutralization channel;
- Collection and consolidation of about 22,000 cubic metres of mine waste;
- Mixing of limestone with the mine waste material at a rate of mix of 0.5 percent by weight (10 kg per cubic metre of waste);
- Placement of 6,600 cubic metres of glacial till cover;
- Construction of 210 m of lined diversion ditch within the pit floor area;
- Construction of a limestone flow-through dam as a temporary pH control measure.

Wet weather towards the end of the 1988 construction season halted till placement with only about 40 percent of the design volume of till placed. The till cover will be completed during the 1989 construction season.

Conclusions

It was recognized that disturbance of the waste rock during excavation and recontouring would result in flushing of additional acid generated products when precipitation or groundwater subsequently flowed through the waste rock. To suppress these effects, the designs for the minesite reclamation required that finely ground limestone be spread over the surface receiving waste rock and be mixed with any waste rock which was moved. Provision was made to monitor pH in the stream below the East Dump and for dosing the stream with sodium carbonate, to increase pH, in the event that construction significantly increased the acid drainage.

As mentioned earlier, the pH of the seepage water at the toe of the East Dump, prior to construction, averaged about 3.3. During recontouring and placement of waste rock, spot pH measurements of discharge from the sump pipes indicated pH values in the order of 5.1 to 5.5. It was concluded, therefore, that the limestone addition was successful in buffering and increasing pH, at least during the construction phase. The provision for dosing the stream, as a pH control measure, was not used.

The B.C. Water Management Branch has sampled water from the seeps and in Pyrrhotite Creek prior to and during the 1988 construction activities. However, the period of record including and following the 1988 construction is too short to conclusively demonstrate an improvement in water quality. Further, because the till cover was not completed to the thickness required in the design, the effectiveness of the cover is, as yet, difficult to assess.

The activities planned for the 1989 season involve completion of the till cover, construction of a permanent diversion channel, a groundwater study and placement of a till cover over the pit floor area between the proposed diversion ditch and the existing dump.

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GOLD TAILINGS RECLAMATION IN SOUTH AFRICA[1]

by

JJP van Wyk[2]

Abstract. This paper deals with the history of rehabilitation (reclamation) on gold mine wastes since the beginning of research in 1932, to large scale experiments during the 1950's and implementation since the 1960's.

It describes the basic philosophy, techniques, methods and treatments followed by the Vegetation Units of the Chamber of Mines and that of Rand Mine Properties which establish vegetation on the tops of slime dams under dry land conditions, whilst using irrigation on the sides of slime dams for leaching, to raise the pH, for the establishment of vegetation.

It also elucidates some of the current research done by the Institute for Reclamation Ecology of the University of Potchefstroom with regards to the rehabilitation of the sides of slimes dams under dry land conditions on "old" slimes dams as well as newly constructed slimes dams due to recycling of "old" sand dumps and slimes dams.

Fairly successful dry land establishment experiments on a slime dam currently under construction from recycled material will be discussed.

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Introduction

Grange (1973) stated that more than 3 billion tons (3×10^9) of rock have been brought to the surface and crushed for gold extraction, and virtually all have been deposited on the surface as sand dumps prior to 1921, and since then as slimes deposits. The combined area already exceeded 80 km^2 in 1973.

The advent of mines caused the development of cities and towns and the air-borne dust created a major nuisance and traffic flow problems.

By 1932 the late Prof Phillips and the late Mr W H Cook started with basic research for the Chamber of Mines. According to James (1966) deposits were originally be considered to be similar to that in semi-desert regions. Seeds of plants used for desert reclamation were imported from various parts of the world. Only two species were found to be successful.

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[1] Paper presented at the 1989 joint conference of the Canadian Land Reclamation Association and American Society for Surface Mining and Reclamation, Calgary, Alberta, August 27-31, 1989.

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Consequently it was decided to try and modify the substrate to such an extent that more acid tolerating drought resistant commercially available species would grow.

Research during the early 1950's, using a cocktail of twenty-one species, yielded partially successful results. It was only since 1958 realised that the high pyrite content of the slimes caused vegetation growth failure despite large applications of lime.

Therefore a procedure was developed using fine water sprays for leaching the acidity from the surface layers into the more alkaline material below. Currently leaching is maintained for eighteen months to two years.

By 1968 the Vegetation Unit of the Chamber of Mines has grassed sufficient sand dumps and slimes and Rand Properties decided then on the formation of their own Vegetation Unit.

The Institute for Reclamation Ecology of the Potchefstroom University started with dryland establishment experiments using only native grasses and heavy liming during 1984 as will be discussed later in this paper.

Reclamation procedures of the Vegetation Units of the Chamber of Mines and Rand Mines Properties

Both Vegetation Units operate on fairly parallel procedures with substrate preparation, water control measurements, fertilizing, establishment, leaching, and maintenance.

The information with regards to the procedures followed by the two Vegetation Units is adapted from Cook (1985) and slightly altered and expanded by the second author.

Gold Tailings Reclamation in South Africa

Introduction

This paper is partially adapted from B J Cook (1985).

Under the guidance of the late Mr W H Cook establishment techniques evolved from:

- The early 'seed bed preparation' method as originally developed for the vegetation of slimes dam sides, to
- the 'minimum cultivation' method in which buttresses were 'split' and collapsed into adjacent gullies which in turn were blocked at intervals with bales of veld grass to prevent erosion, to
- the 'no cultivation' method in which the surface of the slimes is not disturbed at all, except where gullies are exceptionally big.

Also under the guidance of Mr Cook, maintenance of vegetation has evolved from a general annual application of fertilizer to the situation where vegetation on the sides of a slimes dam and sand dump is fertilized by hand on a selective basis - Stoloniferous varieties only!

The need for rehabilitation

Slimes and sand dumps are rehabilitated to satisfy the requirements of the Air Pollution Act and the Water Pollution Act - as cost effective as possible and to the most environmentally satisfying aesthetical appearance, and by controlling the movement of all water on and around the dumps. The success of these efforts can be judged by the commercial and industrial activity and by the establishment of prime residential townships in areas which before 1960 (the leeward sides of very dusty mine dumps) were extremely hostile environments.

Rehabilitation methods as practised today

The rehabilitation of residue deposits proceeds as follows:

Prevention of water pollution - slimes dams

The first step taken is to prevent water pollution. While the mine is still operating any water on the surface of the dam is drawn off through the penstock pipe and discharged into the return water dam from where it is treated, if necessary, and recycled. Water falling on the side of the slimes dam is collected in paddocks at the base of the slimes dam where it is allowed to evaporate or is gravitated to the return water dam.

At closure, however, the procedure changes. A wall, one metre high and one metre broad at the crest, is pushed up by bulldozer around the perimeter of the dam. The slime used to construct the wall is lightly compacted by tamping the material with the bottom of the bulldozer blade.

Similar walls are constructed on contour on the top of the dam. These start at the penstock and proceed outwards at 0,5 m vertical intervals. The top of the slimes dam is thus divided into a series of paddocks - each one isolated from its neighbour by a one metre high wall. The walls are always constructed by pushing from the upstream side so that the resulting profile has the slime at the natural angle of repose on the downstream side and gently sloping at approximately 1:3 on the upstream side. Thus any water impounded does not rest hard up against the base of the wall.

Water movement within the paddock is further impeded by 'ridge ploughing' the floor of the paddock - on contour. This is done by means of a potato or tobacco ridger which leaves ridges and valleys about 50 cm high and about 50 cm apart. Rainwater thus stays where it falls and cannot start erosion by moving across the surface of the highly erodable slime.

The penstock is isolated only by means of the contour walls and by blocking the inlet. The downstream exit of the penstock pipe is never blocked and thus there is no possibility of a head of water building up within the pipes and the side of the slimes dam being eroded when the pipe fails due to old age or corrosion.

After closure, rainwater falling on the sides of the dam is collected in paddocks around the base of the dam and evaporated. The paddocks are sized so as to contain and evaporate water resulting from a 1 in 100 year storm. Usually on the Witwatersrand this requires that the paddocks have the same area as the plan area of the sides of the slimes dam and that the walls are sufficiently high to enable 0,5 m depth of water to be stored within the paddock, plus 0,5 m freeboard.

Where breaks have occurred in the sides of a slimes dam they are isolated from surface water by the perimeter wall around the top. Another wall is thrown across the base of the break to impound rainwater that falls within the break.

Prevention of water pollution - sand dumps

On sand dumps the permeability of the sand is so great that rainwater can drain slowly down through the dump and flow out through low spots in the base, causing localised pollution problems. This is countered by impounding the seepage in paddocks as close to the dump as possible and allowing it to evaporate.

Prevention of air pollution

Generally all slimes dams, (tops and sides), and sand dumps are vegetated to prevent air pollution. As slimes oxidises it loses its cementing properties and becomes very susceptible to wind and water erosion. The oxidised material is easily vegetated. In fact, if this material remained in situ, slimes dams and sand dumps would probably be self vegetating. On sand dumps wind erosion is prevented by the construction of reed paddocks. On slimes dam tops ridge ploughing is most effective in preventing wind as well as water erosion. The oxidised slime collects in the valleys between the ridges. On windy days the only dust blowing off a ridge ploughed top seems to come from the smooth access roads and not from the ploughed surface.

The oxidised material in the valleys between the ridges forms an excellent seed bed and vegetation of the top under dryland conditions is usually possible after a top has been ridge ploughed for two seasons.

Vegetation of the sides of slimes dams

The 'no cultivation' method is used to establish vegetation on the sides of slimes dams. Vegetation proceeds as follows:

- Leaching equipment is erected. This consists of a number of 20 mm polythene water pipes, 100 m long, erected parallel to each other, on contour, 3 m apart. Micro jets are screwed into the pipes at 2,5 m intervals. The pipes are erected on stakes approximately 1 m high and each pipe is individually controlled by a valve.
- Bales of mulch, or orange pockets in which a mixture of stoloniferous grass shoots which has previously rooted in soil, are placed in the erosion gullies at frequent intervals so as to impede the velocity of rainwater and prevent erosion until the vegetation is established.
- Calcitic lime at 7,5 t/ha and superphosphate at 300 kg/ha is broadcast by hand over the area.
- A mulch of veld grass preferably cut in the seed ripening stage in an area where a variety of grasses - particularly *Hyparrhenia hirta* - grow, is spread at a rate of 200 bales/ha. If the pH of the slime is below 3, the mulch is spread at a rate of 400 bales/ha.
- Leaching is started. Water is sprayed onto the surface of the slime from the micro jets at a rate that is just below the optimum rate of infiltration into the slime. In other words the water must all be absorbed into the slime with no run-off. On occasions washing powder is used to improve the penetration of the water into the slime.
- Handplanting. The seed of most of the grasses used for vegetation is commercially available. There are some species however that are so effective, and for which seed is not commercially available, that they are raised vegetatively in separate containers in a nursery.

Some of these varieties area:

Name	No of plants/ha
Cynodon aethopicus	1440
Cortaderia selloana	350
Pennisetum macrorum	350
Pennisetum clandestinum	700
Populus canescens	175
Carpobrotus edulis	80
Coronilla varia	100

- The seedmix is prepared and sown. Legume seeds are inoculated and all the seeds are mixed together into one large cocktail. Agricultural lime is used as a distribution and germination aid and approximately 100 kg of calcitic lime is thoroughly mixed with the seed before sowing.

The following seedmix is used:

Name	Quantity (kg/ha)
Cynodon dactylon	2,5
Eragrostis curvula	1,25
Dactylus glomerata	2,5
Chloris gayana	2,5
Festuca elatior	2,5
Agrostis tenuis	2,5
Poa pratensis	1,25
Lolium perenne	1,25
Bromus catharticus	1,25
Atriplex semibocata	1,0
Trifolium repens	1,25

Medicago sativa	1,25
Melilotis alba	1,25
Brassica nupus	0,25

- Four days later 2:3:2(22) fertilizer is applied at 300 kg/ha and repeated when the seedlings reach the 3rd leaf stage - about 3 weeks after sowing.

Post germination treatment

Rape (*Brasica nupus*) is included in the seedmix as an indicator plant and gives early warning of phosphate deficiencies or of the return of acid conditions. Immediate corrective action to rectify conditions is always taken by applying either more superphosphate or agricultural lime. If it is possible to grow poor rape it is possible to grow good grass!

Leaching continues until a good grass cover has been established and then a 'toughening-up' process starts during which the application of water is decreased gradually. After no leaching has taken place for a period of at least two months, the leaching pipes are removed if no severe stress signs are apparent in the vegetation.

Vegetation of the tops of slimes dams

All vegetation is established on the tops of slimes dams under dryland conditions.

After water control measures have been completed on the top, the floors of the paddocks are ridge ploughed once per annum for at least two years.

Ridge ploughing usually takes place during the winter months just before the onset of the spring winds. After the second ridge ploughing is completed, trial plots, approximately 10 m x 10 m are established on the top at a density of roughly one plot/25 ha. These plots are fertilised, limed and sown using the standard seed mix during favourable weather conditions in early spring and if successful, vegetation of the whole of the top proceeds during summer in the following manner:

- During favourable weather conditions calcitic agricultural lime at a rate of 7,5 t/ha and superphosphate at 600 kg/ha is disced into the surface.

- The seedmix is broadcast over the area and rolled using a land roller to corrugate the surface and to ensure a good seed/soil contact.

- Four days after sowing 2:3:2(22) fertilizer is applied at a rate of 300 kg/ha. This application is repeated when the vegetation reaches the third leaf stage.

- Once the vegetation is well established - 4 to 5 weeks after germination - urea is applied at a rate of 50 kg/ha and repeated about 10 days later.

- The seedmix used is the same as is used on the sides of the slimes dams, with the addition of some tree seeds, particularly *Acacia baileyana*, *Acacia melanoxylon*, and *Gladitia tricanthos*. The *Acacia* seeds are boiled in water for two minutes to stimulate germination.

Aftercare -- maintenance

Slimes dams tops. The only aftercare provided for the tops of slimes dams is the annual discing of 5 m wide firebreaks around the top perimeter of the dam and across the top so that it is divided into paddocks approximately 2 ha in area. Bluegum (*Eucolyptus*) tree seedlings are also removed wherever they are found growing on residue deposits. They spread quickly and their presence rapidly leads to a deterioration of the other vegetation.

It has not been necessary, on any of the vegetated slimes dams tops under our control, in the last 15 years, to apply any maintenance fertilizer once the vegetation has been established.

Slimes dams sides. It was initially normal practice to fertilize the whole side where weak vegetation was apparent using a mixture containing 2:3:2(22) + 0,5% Zn at 150 kg/ha; urea at 50 kg/ha; and potassium chloride at 25 kg/ha. This was initially spread by hand, then by helicopter and eventually a fixed wing crop sprayer aeroplane.

The problem with giving a general application to the side was that the canopy cover grasses responded rapidly to the application and the stoloniferous varieties were suppressed. This resulted in a very lush growth of vegetation which consisted basically of very hungry grasses which required some form of veld management if they were not to go moribund. A fire during the winter was almost impossible to fight because of the lush growth. The fire tended to be a very 'hot' fire and usually severely damaged the vegetation. As a result of the damage the area would require fertilizing again the following season and this started a cycle of fertilizer, burn, fertilizer, burn, etc.

To overcome this a system was developed of applying fertilizer selectively by hand, to stoloniferous varieties only, instead of a general application. This obviously results in the promotion of the stoloniferous varieties at the expense of the canopy type varieties. It was found possible to change the predominant vegetation on the side of a slimes dam from one which is hungry, a fire hazard and susceptible to damage by fire, and which requires periodic management to prevent moribund conditions, to one which has low nutrient requirements, appears to recover well if burnt, and requires minimal attention.

Local grasses for which seeds are not commercially available also appear to move in more readily where they are not in competition with a heavy canopy-type cover.

There is also a considerable saving in fertilizer when applied selectively.

It takes a trained team consisting of a supervisor and 15 labourers about one month to selectively fertilize the sides of the 50 slimes dams representing 250 ha of sides.

Advantages of establishing vegetation on the sides of slimes dams using the 'no cultivation' method as opposed to seed bed preparation method

- There is a significant saving in cost.
- There is no storm damage.
- Less leaching is required.
- The 'no cultivation' method is not affected by the steepness of the slope of the slimes dam.
- Reshaping costs are saved.
- A 'permanent cover' is established more rapidly using the 'no cultivation' method.

Costs

Costs of vegetation vary from site to site but can be expected to fall within the following ranges if the work is done by the local workforce and the cost of water is excluded:

* Slimes dam tops	R1000 - R1500/ha
* Slimes dam sides	R800 - R1200/ha

For sides of slimes dams an amount of R200/ha/annum should be set aside for maintenance of vegetation for five years after establishment.

Conclusion

The well vegetated mine dumps on the central Witwatersrand bear testimony to the fact that South Africa's prominent gold industry need not have a dark side.

The mine dumps, those very visible relics of past mining activity, need not be considered liabilities in the city life. The challange to overcome the environmental problems has uncovered an opportunity to bring nature back into the city (figure 1).

We have been able, at reasonable cost in financial, time and effort terms, to establish a vegetative cover on the dumps that is permanent, pollution free, aesthetically pleasing, cost effective and which is bringing widlife back to an area from which it has been excluded for many decades.

Dryland rehabilitation research on old slimes dams

Due to space limitation this presentation will be brief and to the point.

Dry land establishment on the sides of two still active slimes dams in the Western Transvaal is currently in the first and third season (figures 2 and 1) after establishment respectively.

Two of the six treatments yielded satisfactory results and will briefly be discussed.

Horizontal trenches, spade deep and spade wide, were dug at 1,0, 1,5 and 2,0 m vertical intervals starting at the top of the dam. Lime was applied in these trenches to the equivalent of 6 t/ha. The equivalent of 2 t/ha was evenly spread by hand.

The trenches were filled with grass straw from nearby seed production lands and therefore contained some seed. The straw was slightly compacted by walking over the surface.

Fertilizer and seed were applied by hydroseeding, after which a 100-200 mulch "blanket" was spread on by means of a hydroseeder. The mulch was tackyfied by means of butumen in the first experiment and with a local manufactured bonding chemical with a brand name of Multac Type 1 in the 1988/89 experiment (figure 2).

In all cases where the mulch blanket could be kept intact and in place for the first season a satisfactory, but not a uniformly even, cover developed. The stoloniferous grasses are currently beginning to invade the bare buttresses where initial establishment did not take place satisfactoraly.

The difference (rather fairly similar results) between dryland establishment, and establishment under irrigation (for leaching purposes) is obvious in figure 1.

It is not yet known if successful dryland establishment could be applied generally as some slime dams might have a higher pyrite content as the ones selected for these experiments. The cost of dry land rehabilitation is estimated at 50% of the establishment under leaching with irrigation.

Fertilizer

2000 kg/ha of lime was applied on the surface and 6000 kg/ha in the furrows. In addition 400 kg/ha superphosphate, 400 kg/ha KCl (Potassium choride), 200 kg/ha 2:3:2(22) (NPK), and 100 kg/ha limestone ammonium nitrate was applied.

The seed cocktail (±40 kg/ha) represent the following species:

Anthephora pubescens
Cynodon dactylon
Chloris gayana
Cenchrus cilliaris
Digitaria eriantha
Paspalum dilitatum
Hyparrhenia hirta
Atriplix semibocata
Atriplex numularia
Stylosanthus sp.
Trifolium sp.
Vicia sp.
Medicago sativa
Tritium sp.
Plus a mixture of pioneers and various *Eragrostis curvula* "ecotypes".

The exact amount of seed for each species cannot be determined as some of the seed was collected in mixed stands in natural veld by harvesting and by means of suction harvest from the ground.

Figure 1. (A)

A permanent vegetation cover on the side of a slimes dam three seasons since establishment. Dry land establishment was used on the front 100 metres and irrigation on the rest.

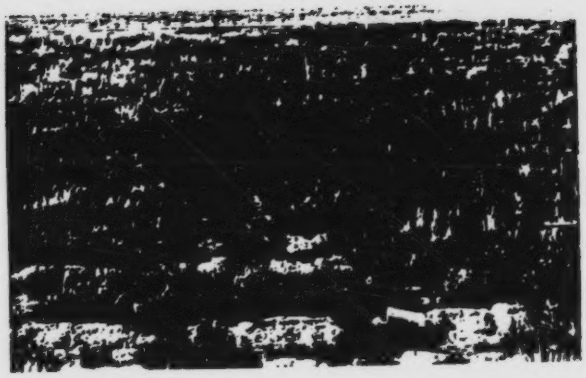

Figure 1. (B)

A permanent vegetation cover on the side of a slimes dam three seasons since establishment. Dry land establishment was used on the left side and irrigation on the right hand side.

Figure 2.

Dry land establishment four months old. Establishment is good in the horizontal trenches and vertical gullies. Stoleniferous species only covers the buttresses from the second and third season onwards.

Dry land rehabilitation research on freshly recycled slimes

The recycling of sand dumps and slimes dams has become a major industry during the last decade. It is estimated that about 50% of all existing slime deposits will be recycled for gold and acid extraction.

The Institute for Reclamation Ecology is acting as Ecological Consultant for one of the major recycling companies operating in the Eastern Suburbs of Johannesburg.

The slime after extraction of gold and sulphuric acid, is pumped as a slurry to a rural area some 50 kilometres distant from the downtown Johannesburg area.

The slimes dam will ultimately be about 2000 ha in size with a variable height due to undulating terrain on which it is constructed. The average height is expected to be 60 metres.

The construction method is by means of cyclones and the side slopes are ±30°; not too steep to rehabilitate. Despite the recycling the pH varies between 4-4,5.

After three years of research, soil amelioration, species selection and establishment techniques have been worked out (figure 3), and implementation was started during the 1988/89 growing season.

Tailing amelioration and fertilization

Two tons of straw mulch was spread per ha, followed by the application of 400 kg/ha superphosphate; 400 kg/ha potassium chloride (KCl) and 200 kg/ha 2:3:2(30) + Zn and 6 tons of lime per ha. All the material was rotivated into the tailings to a depth of 100-150 mm. Hydroseeding was done immediately after the rotivating to ensure that the seed is placed on a freshly disturbed coarse seedbed. The same seed cocktail as already mentioned was used.

Pioneer grasses of which seed is produced by the Institute represent *Rhynchelytrum repens*, *Enneapogon cenchroides*, *Chloris virgata*, *Heteropogon contortus*, *Stipagrostis uniplumus* and various *Aristida* species. These species were originally collected in semi-desert conditions and are extremely drought tolerant.

The cocktail also contains 10-12 new genetic lines (not yet registered as ecotypes) of *Eragrostis curvula* (weeping love grass) specially selected by this Institute for rehabilitation purposes. They are in all respects superior to the commercially available *Eragrostis curvula* var. *Ermelo*.

In experiments, this cocktail yielded a very effective permanent cover (figure 3) and no maintenance had to be applied since establishment in 1985/86.

One of the recent "discoveries" was the observation that one of the "new" genetic strains of *Eragrostis curvula* was escaping from the experimental plots and invading totally untreated slimes (figure 3, right hand side of the road).

The vitality of these plants in treated and untreated slimes is exactly the same (figure 4).

Seed is currently produced of this new strain which will soon be registered as a new variety.

References and additional reading materials

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Figure 3.

Successful experiments left of the road side established in 1985/86.
Invasion of a "new" genetic strain of Eragrostis curvula on untreated slime (dense stand) right side of the road.

Figure 4.

"New" genetic variety of Eragrostis curvula. Left, mature plant growing in totally untreated slimes. Middle and right young plants in treated (middle) and untreated slimes. The vitality of the young plants are basically the same.

CONFLICTS IN THE RECLAMATION OF ABANDONED METALLIFEROUS MINE SITES IN THE UK[1]

by

Ivor G. Richards[2]

Abstract. Abandoned metalliferous mine sites are sources of heavy metal pollution and are also landscape scars. A large number of these sites are to be found in Wales and are becoming the latest focus of attention in a long running programme of reclamation of industrial dereliction. Interest in the sites is growing however because of their ecological and historical value and reclamation schemes are having to be designed to take account of the views of these special interest groups.

Additional Key Words: ecology, industrial archaeology, interpretation.

"The grass, forerunner of life has gone,
But plants that spring in ruins and shards
Attend until your dream is done":

Gordon Bottomley
To ironfounders and others.

Introduction

Wales was a major centre of metal mining in the United Kingdom, producing about 25% of the UK's lead and 40% of its zinc between 1845 and 1930 (Lewis 1967). Copper was also a major product and silver and gold were produced in smaller quantities. Many mines were small. The old County of Cardiganshire in Wales which accounted for between 7 and 9% of the UK's production of lead between 1840 and 1880 had over 200 small mines (Burt et al 1987). There were however some large mines in Wales. Parys Mountain, worked for copper since Roman times by open pit and deep mining methods, is estimated to have produced 130,000 tons of copper metal from around 3 million tons of ore (Williams 1980).

The mine is however by no means exhausted. In 1989 a shaft is being sunk by Anglesey Mining, a subsidiary of Imperial Metal Corporation of Vancouver, to prove an orebody and hopefully herald the start of a new era of mining at this site.

Site characteristics

Water power was the major means of driving machinery in the metal mines of Wales and although coal-fired engine houses were introduced at many

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sites during the nineteenth century they were not always a success. Poor communications with coal producing areas were probably a significant factor in the case of many of these failures to take advantage of technological advance. The large scale use and reliance on water resulted in ore processing facilities being sited near rivers. Considerable skill, ingenuity and effort was required to construct leats, dams and tunnels in order to link catchments and control water flow. Legal disputes over water rights must have been as fierce as those over mineral rights. Because of all this work the mines affected a much greater area of land than the actual site of extraction and processing.

The fortunes of the mines were forever fluctuating in response to world metal prices and as a result mine structures were continually being adapted, abandoned or renovated. Spoil disposal always has been a problem, and on cramped sites mine spoil and process waste were often deposited on previously used areas, obliterating shafts, buildings and many other features. As a result there is a legacy in Wales, which is repeated elsewhere in the UK, of:

- evidence of pre-christian working at many sites.
- substantial remains of seventeenth and eighteenth century working at some sites.
- remains of nineteenth and early twentieth century workings at most sites which were worked in this period.
- artefacts left underground - some substantial pieces of machinery such as water wheels.
- artefacts above ground, some covered by waste, other not so covered. Some of these would be of biodegradable material such as wood or leather.
- open shafts and partly filled or covered shafts.
- surface features in the surrounding areas, packhorse trails, tramways, railways, leats and so on.

A further important feature of these sites is that having been abandoned eventually, and lying in remote areas, that is remote in UK terms, they have provided opportunities for refuge for wildlife when surrounding land was being used for agriculture, forestry or development. In addition these sites contained materials with unusual properties, high or low pH and high levels of metals for example, and these conditions, coupled with little or no disturbance, created situations where rare plants would become established. Heavy metal tolerators are a particularly important group of such plants, other rare higher and lower plants can be found in the sites, expecially in limestone areas.

Open shafts and mine workings in the UK have also become colonised by bats which are now a protected species, and hence have to be given special consideration and accommodated in any proposal which could involve their disturbance or changes in their environment. Closing of shafts and adits can change air flows in mine workings for example.

Areas of conflict

Abandoned metalliferous mines are obviously a cause for concern because they can be dangerous and are a ready source of heavy metals which will degrade the environment. Because the processes used at the oldest mines were particularly inefficient it is not unusual to find amongst their waste dumps tailings containing as much as 5% of lead and 12% of zinc. Quite small mines, occupying say 5.0 hectares or less can therefore be significant sources of pollution locally and should be reclaimed on this account. Yet it is these small sites that are frequently found to be the most interesting on archaeological and ecological grounds. Of course the larger more modern sites of the twentieth century pose the bigger threat in terms of pollution overall, but unless they have had a long history of working, the conflict between the 'reclamation brigade' and the conservationists is nothing like as intense as in the other category when a reclamation scheme is being considered.

Conflicts between these opposing groups can occur at different levels and for different reasons. The main purpose in carrying out a reclamation scheme is public protection, that is;

- removal of a source of pollution,
- reduction in the risk of personal injury to uninformed or chance visitors,
- landscape improvement.

To achieve these aims site regrading, control of surface and perhaps underground waterflows, demolition of unsafe structures, shaft and adit treatment and finally stabilisation by means of surface capping and vegetation all figure to a greater or lesser extent in a reclamation proposal. Clearly a straightforward, no nonsense, wipe it all away approach has some appeal - speed and probably economy - but is insensitive to other interests, for example:

- earthmoving and drainage works in areas of high wildlife value,
- earthmoving and drainage works in areas of high industrial archaeological value,
- shaft capping where bats are involved,
- shaft capping where the shafts are of industrial archaeological importance,
- demolition of insecure but interesting structures,
- introducing a stable but bland vegetation cover.

Interestingly further conflicts then arise between the parties involved:

- underground workings are attractive to cavers who see industrial archaeology as an added bonus, but they disturb the bats,
- industrial archaeologists wish to see remains stabilised, walls repointed (using the correct mortar of course) shaft collars repaired and so on, but frequently these featues support the rare plants which are of interest to the ecologist. The situation becomes even more complicated when lime tolerant plants establish themselves in the mortar of old mine buildings in Mid-Wales where acidic rocks and soils predominate.
- Some schools of thought would have nothing done at all at these sites, others view the sites as assets to be interpreted and developed as areas of historical interest for the benefit of the general public.

In order to resolve these conflicts it is clear that the reclamation design team needs to have a detailed knowledge of the site. It is common now for the site investigation teams to include an industrial archaeologist, ecologists, soil scientists, engineers and landscape architects, much the same sort of team as would be assembled for the assessment of a new mine.

At the preliminary design stage this same team, ideally, would also be advised on the appropriate level of afteruse for the reclaimed area. New people bringing to the team expertise in tourism, so that a detailed brief can be prepared for subsequent stages of reclamation, interpretation and possible development.

Our philosophy at RML is that at the end of the day every interested party has to "come away" with something, the alternative is an impasse, non-cooperation by one or more groups, and a final design which is forced through by authority after long delays. The design team therefore has to be innovative, constantly positive in its approach, long suffering and above all patient.

Minera Lead Mines

The reclamation of Minera Lead Mines near Wrexham in North Wales,Figure 1, contains all the elements and factors mentioned earlier, especially prolonged use,

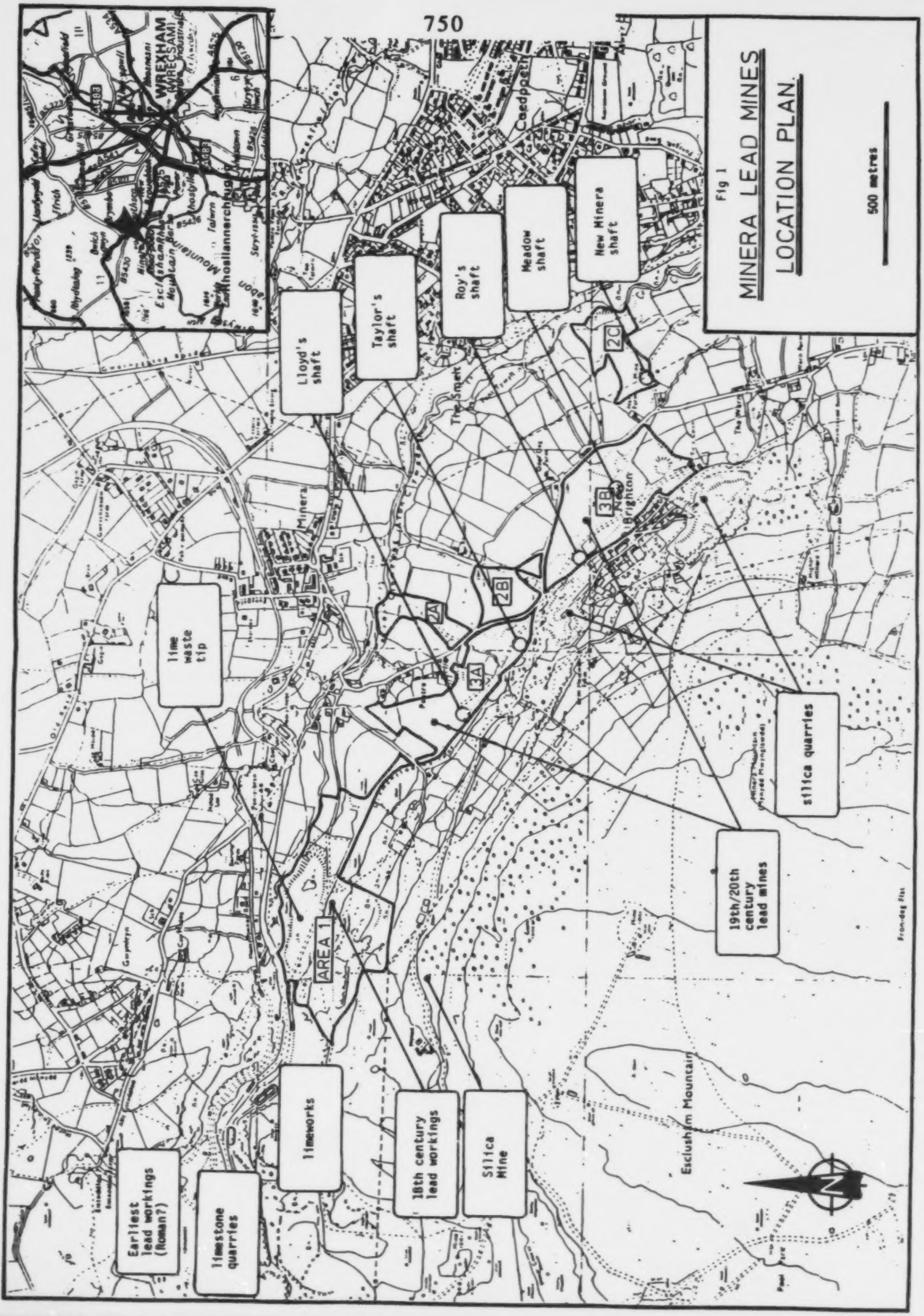


Fig 1

MINERA LEAD MINES LOCATION PLAN.

500 metres
Lloyd's shaft
Taylor's shaft
Roy's shaft
Meadow shaft
New Minera shaft
lime waste tip
silica quarries
19th/20th century lead mines
Earliest lead workings (Roman?)
limestone quarries
limeworks
18th century lead workings
Silica Mine
AREA 1
2A
2B
2C
3A
3B
Minera
New Brighton
The Smelt
Caedpoeth
Esclusham Mountain
WREXHAM (WRECSAM)
N

since the Roman occupation, and a great deal of covering-over in successive periods of activity from the 14th Century onwards.The district has been extensively worked for lead, zinc, limestone and silica. The value of lead extracted alone has amounted to some £60,000,000 at current prices.

Consideration of a reclamation scheme at Minera began in the early 1970's, progress was slow, pending the results of vegetation trials, land acquisition by the local authority, Wrexham Maelor Borough Council, and most importantly, the inclusion of metalliferous mines in the Welsh Development Agency's programme of reclamation of derelict land.

During these years knowledge of metal tolerance in plants and related topics grew, and an increasingly more sensitive approach was looked for in the design of reclamation schemes. In many respects it was fortuitious that the reclamation scheme at Minera did not go ahead in the early years, much of what we now regard as of value and interest would have been lost. In 1986, design work was preceded by a very detailed site investigation, an assessment of the ecological and landscape value of the site and the likely level of industrial archaeological interest. The total scheme was divided into 2 phases with the areas which were the worst "polluters" and (hopefully) the least complicated archaeologically dealt with first. In the event, during the phase 1 works, the remains of an interesting halvans plant were found beneath tailings, figures 2 and 3. As a result of this and other finds, careful digging in the phase 2 area, where many more finds were expected, confirmed the positions and levels of buildings and other features. Figure 4 shows the difference in detail contained in Ordnance Survey maps for 1899 and 1966, and can be compared with our scheme survey of the same area, originally at 1:500 scale, figure 5.

This level of information was used in the design of the phase 2

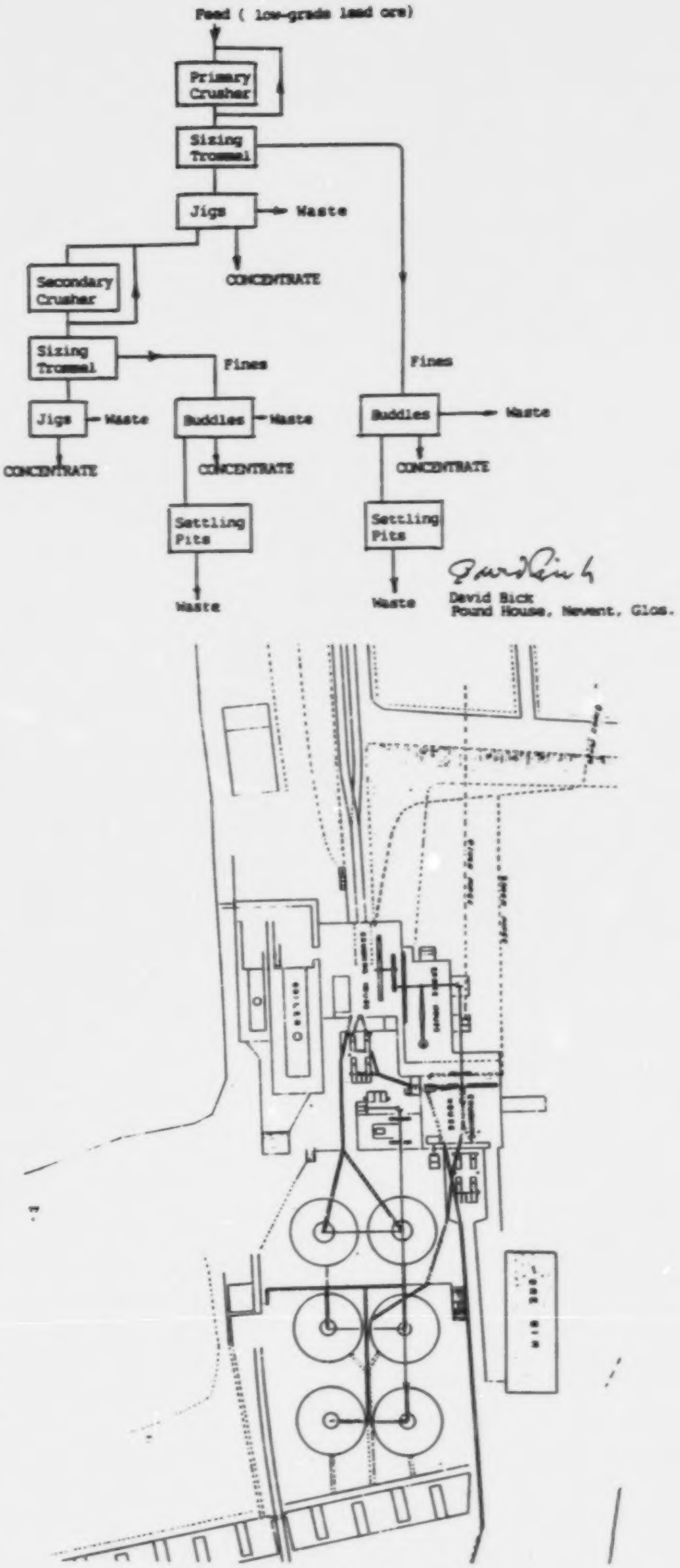

Feed (low-grade lead ore)
Primary Crusher
Sizing Trommel
Jigs
Waste
CONCENTRATE
Secondary Crusher
Sizing Trommel
Fines
Jigs
Waste
CONCENTRATE
Buddles
Waste
CONCENTRATE
Settling Pits
Waste
Fines
Buddles
Waste
CONCENTRATE
Settling Pits
Waste
David Bick
David Bick
Pound House, Newent, Glos.

Figure 2. Minera halvans plant. Interpretation of 1988 excavations by David Bick (above) based on 1874 layout (below)

earthmoving and drainage works which of necessity are far more complicated than those normally encountered in a reclamation scheme. Other novel features of the scheme were;

- areas of wildlife interest, particularly damp willow woodland with a rich ground flora, including orchids, were protected by excluding all civil engineering plant,
- cuttings of metal tolerant willows were taken for planting in the final stages of the scheme,
- the metal rich tailings were brought together in selected areas and sealed against ingress by downward percolating rainwater by using polythene sheeting (phase 1) and sheeting or bentonite slurry in a thin colliery spoil layer (phase 2).
- colliery spoil from a nearby derelict coalmine was used as capping material except in steeply sloping areas (phase 1) where sites were cleaned down to uncontaminated original ground.
- detailed instructions were prepared for the benefit of site supervisors and contractor's staff on the methods to be adopted in excavating around industrial remains.
- the land drainage system was designed to make the best use of old featues such as leats, channels and reservoirs, so that interpretation of the industrial remains would be easier.
- a special study was carried out into methods of accommodating the competing interests involved around shafts. 43 known shafts lie within the scheme boundaries, we believe the actual member could be double that. Figure 6 and 7 show a few pages from our "design manual" dealing with the treatment of disused mine shafts, which has been well received by environmental bodies and industrial archaeologists.
- a master plan was prepared to ensure that the brief for the reclamation scheme fitted the overall concept of creating at least a country park with

Figure 3. Minera halvans plant.
1988 excavations, looking towards the waste heaps which ran down into the valley bottom, these were cleared back to original soil in the reclamation scheme.
Remains of timber frames, channels etc. were widespread, possibly because the toxic metalliferous wastes inhibited bacteriological action.

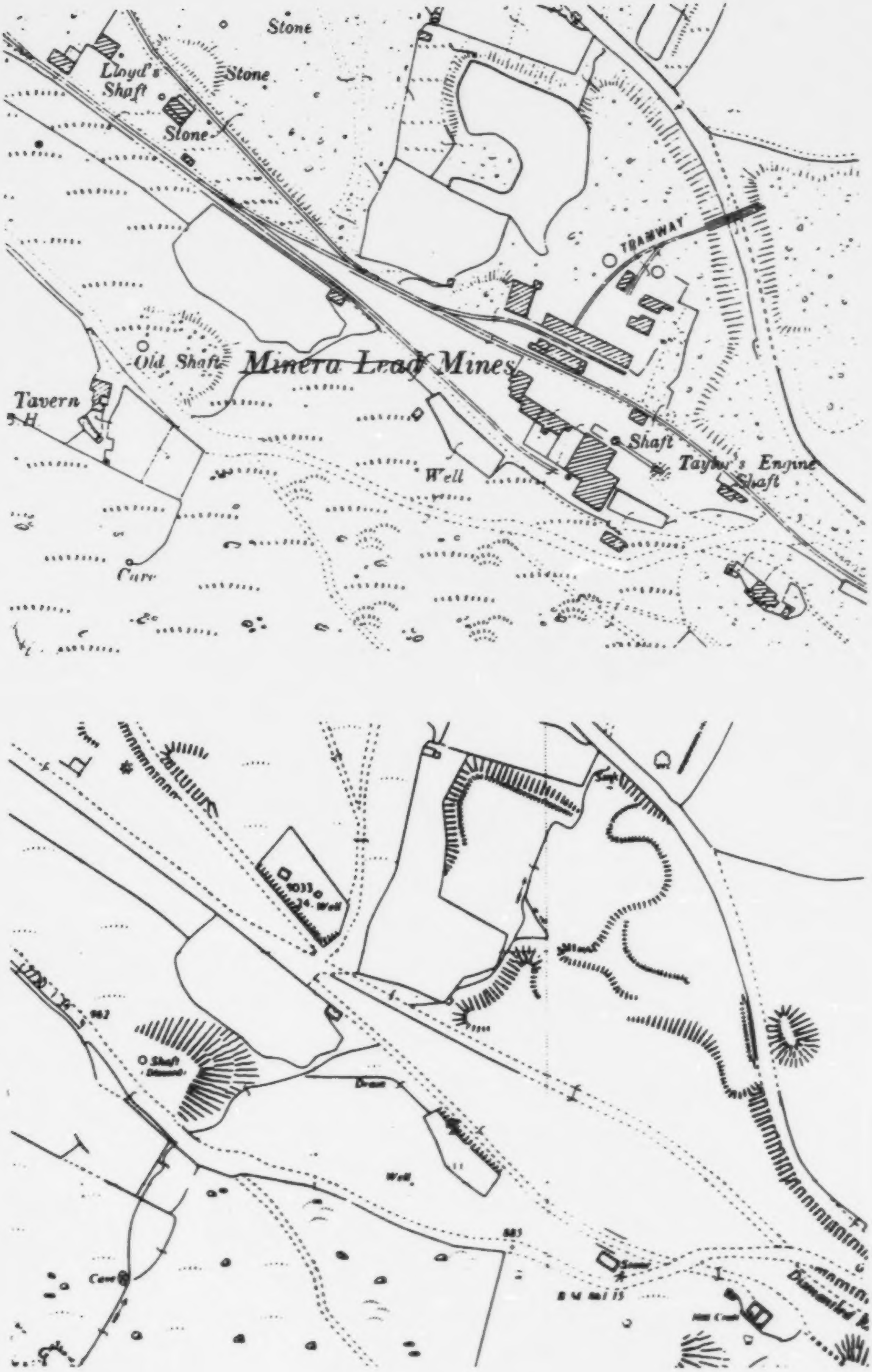

Stone
Lloyd's Shaft
Stone
Stone
TRAMWAY
Old Shaft
Minera Lead Mines
Tavern
P.H.
Shaft
Taylor's Engine Shaft
Well
Cave
Shaft (Disused)
Drain
Well
Cave
Stone
Dismantled R

Figure 4. Taylor's Shaft area of Minera, as recorded by the Ordnance Survey in 1899 (above) and 1966 (below).

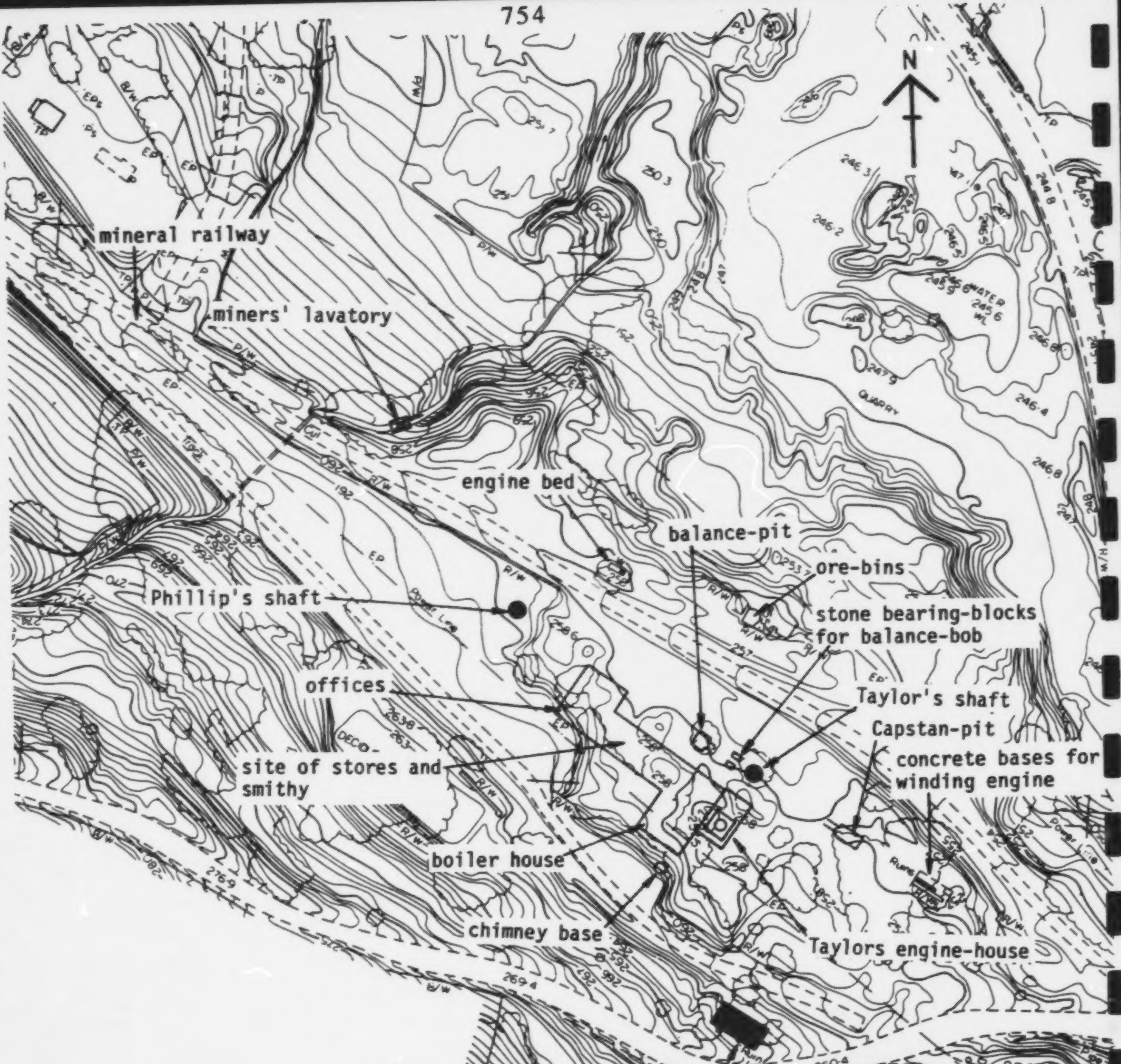
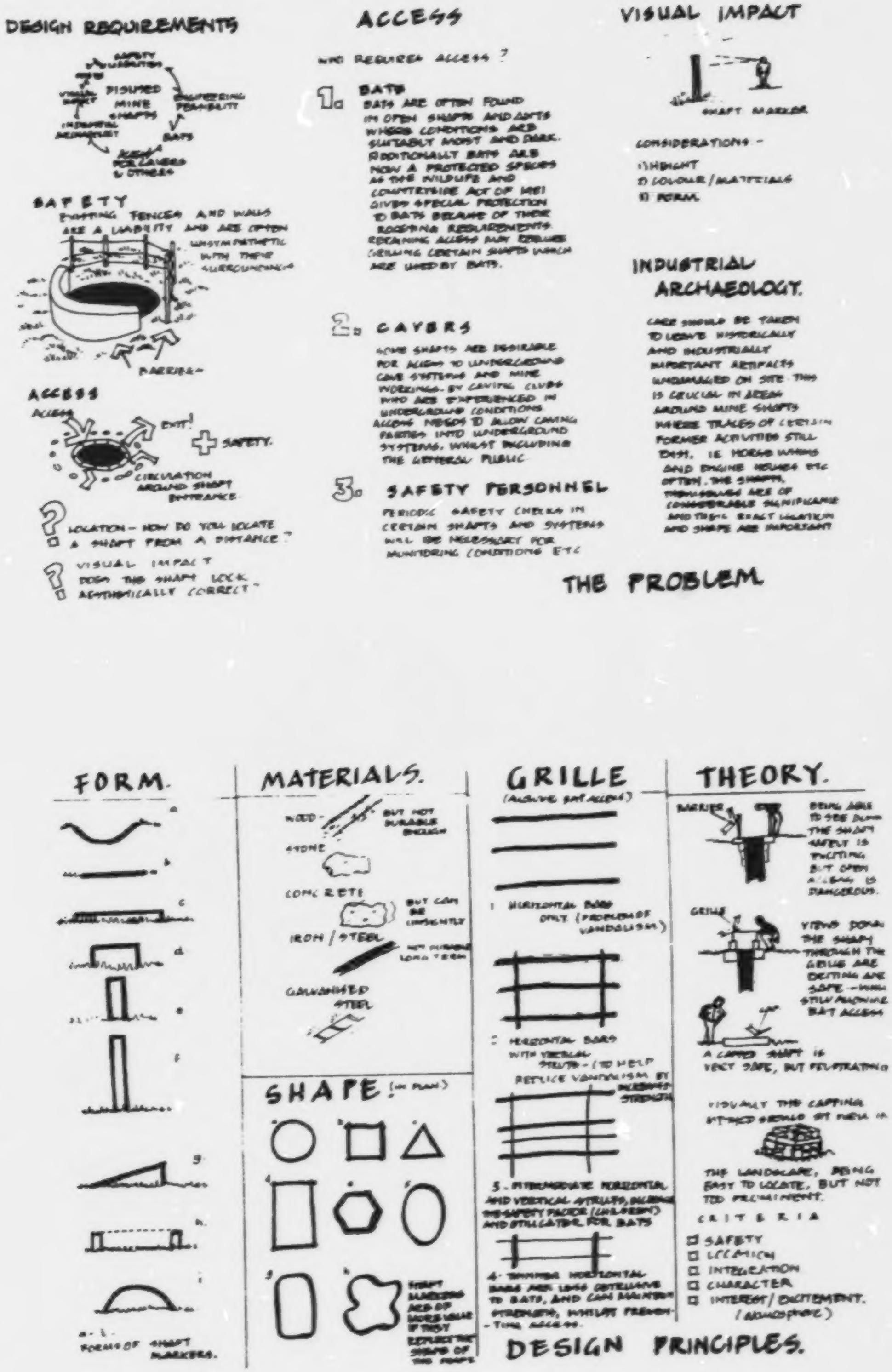

N
mineral railway
miners' lavatory
engine bed
balance-pit
ore-bins
stone bearing-blocks for balance-bob
Phillip's shaft
offices
Taylor's shaft
Capstan-pit
concrete bases for winding engine
site of stores and smithy
boiler house
chimney base
Taylors engine-house
Smithy and mortuary
QUARRY
TAYLOR'S SHAFT AREA
0
50
(metres)

Figure 5. Engineering survey of the Taylor's Shaft area marked up with features of interest.


DESIGN REQUIREMENTS
SAFETY LIABILITY
VISUAL IMPACT
DISUSED MINE SHAFTS
ENGINEERING FEASIBILITY
BATS
ACCESS FOR CAVERS & OTHERS
INDUSTRIAL ARCHAEOLOGY
SAFETY
BARRIER
ACCESS
ACCESS
EXIT!
SAFETY.
CIRCULATION AROUND SHAFT ENTRANCE.
ACCESS
VISUAL IMPACT
SHAFT MARKER
INDUSTRIAL ARCHAEOLOGY.
THE PROBLEM
FORM.
a
b
c
d
e
f
g
h
i
a – i – FORMS OF SHAFT MARKERS.
MATERIALS.
WOOD – BUT NOT DURABLE ENOUGH
STONE
CONCRETE BUT CAN BE UNSIGHTLY
IRON / STEEL NOT DURABLE LONG TERM
GALVANISED STEEL
SHAPE (IN PLAN)
a
b
c
d
e
f
g
h
SHAFT MARKERS ARE OF MORE VALUE IF THEY REFLECT THE SHAPE OF THE SHAFT
GRILLE
(ALLOWING BAT ACCESS)
THEORY.
BARRIER
GRILLE
CAP
DESIGN PRINCIPLES.

EXISTING FENCES AND WALLS ARE A LIABILITY AND ARE OFTEN UNSYMPATHETIC WITH THEIR SURROUNDINGS

? LOCATION – HOW DO YOU LOCATE A SHAFT FROM A DISTANCE?

? VISUAL IMPACT DOES THE SHAFT LOOK AESTHETICALLY CORRECT?

WHO REQUIRES ACCESS?

1. BATS
BATS ARE OFTEN FOUND IN OPEN SHAFTS AND ADITS WHERE CONDITIONS ARE SUITABLY MOIST AND DARK. ADDITIONALLY BATS ARE NOW A PROTECTED SPECIES AS THE WILDLIFE AND COUNTRYSIDE ACT OF 1981 GIVES SPECIAL PROTECTION TO BATS BECAUSE OF THEIR ROOSTING REQUIREMENTS. RETAINING ACCESS MAY REQUIRE GRILLING CERTAIN SHAFTS WHICH ARE USED BY BATS.

2. CAVERS
SOME SHAFTS ARE DESIRABLE FOR ACCESS TO UNDERGROUND CAVE SYSTEMS AND MINE WORKINGS. BY CAVING CLUBS WHO ARE EXPERIENCED IN UNDERGROUND CONDITIONS ACCESS NEEDS TO ALLOW CAVING PARTIES INTO UNDERGROUND SYSTEMS, WHILST EXCLUDING THE GENERAL PUBLIC

3. SAFETY PERSONNEL
PERIODIC SAFETY CHECKS IN CERTAIN SHAFTS AND SYSTEMS WILL BE NECESSARY FOR MONITORING CONDITIONS ETC

CONSIDERATIONS –
i) HEIGHT
ii) COLOUR/MATERIALS
iii) FORM.

CARE SHOULD BE TAKEN TO LEAVE HISTORICALLY AND INDUSTRIALLY IMPORTANT ARTIFACTS UNDAMAGED ON SITE. THIS IS CRUCIAL IN AREAS AROUND MINE SHAFTS WHERE TRACES OF CERTAIN FORMER ACTIVITIES STILL EXIST. IE HORSE WHIMS AND ENGINE HOUSES ETC OFTEN, THE SHAFTS THEMSELVES ARE OF CONSIDERABLE SIGNIFICANCE AND THEIR EXACT LOCATION AND SHAPE ARE IMPORTANT

1 HORIZONTAL BARS ONLY (PROBLEM OF VANDALISM)

2 HORIZONTAL BARS WITH VERTICAL STRUTS – (TO HELP REDUCE VANDALISM BY INCREASED STRENGTH

3. INTERMEDIATE HORIZONTAL AND VERTICAL STRUTS, INCREASE THE SAFETY FACTOR (CHILDREN) AND STIMULATOR FOR BATS

4. THINNER HORIZONTAL BARS ARE LESS OFFENSIVE TO BATS, AND CAN MAINTAIN STRENGTH, WHILST PREVENTING ACCESS.

BEING ABLE TO SEE DOWN THE SHAFT SAFELY IS EXCITING BUT OPEN ACCESS IS DANGEROUS.

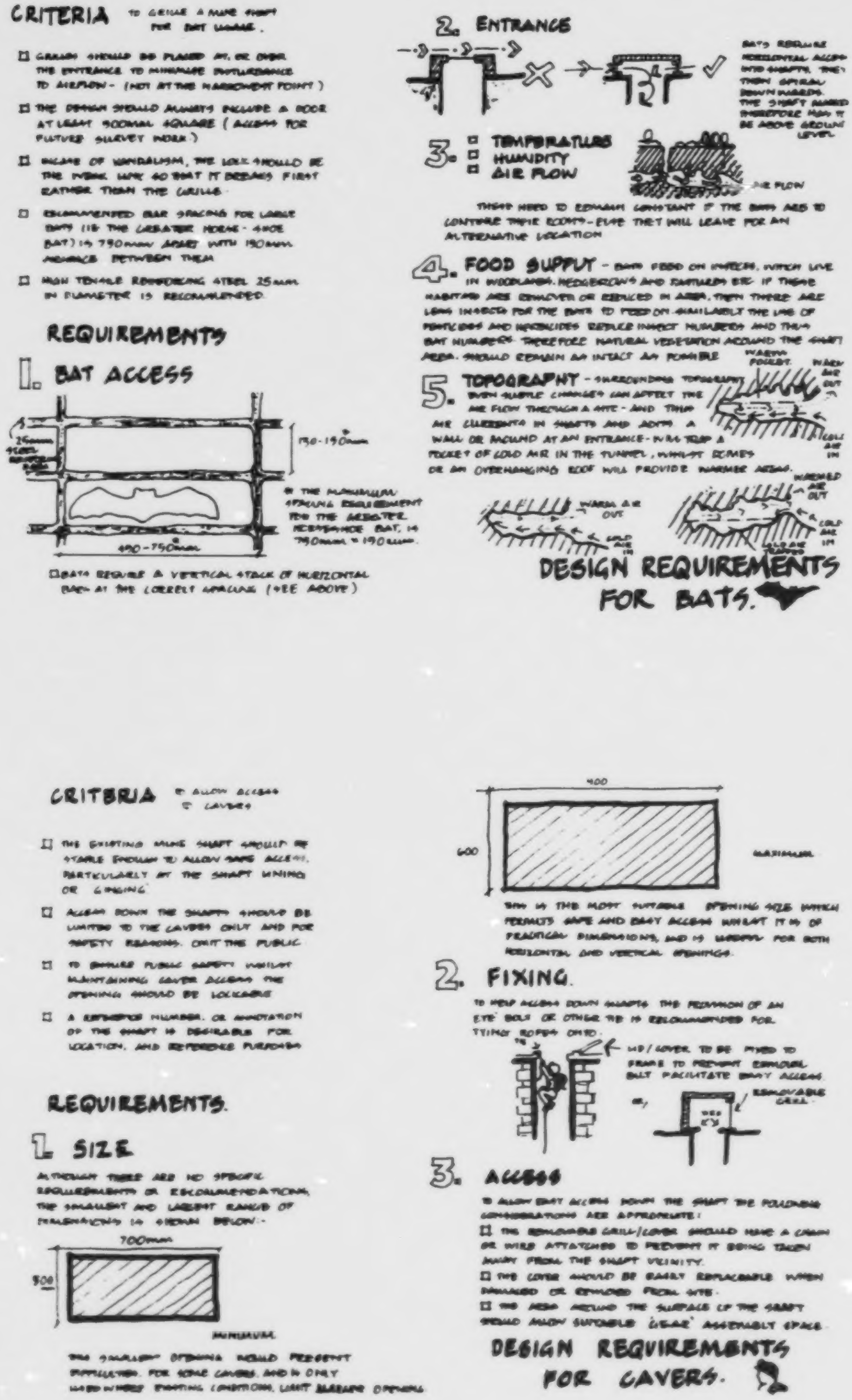
VIEWS DOWN THE SHAFT THROUGH THE GRILLE ARE EXCITING AND SAFE – WHILE STILL ALLOWING BAT ACCESS

A CAPPED SHAFT IS VERY SAFE, BUT FRUSTRATING

VISUALLY THE CAPPING METHOD SHOULD SIT WELL IN THE LANDSCAPE, BEING EASY TO LOCATE, BUT NOT TOO PROMINENT.

CRITERIA
- ☐ SAFETY
- ☐ LOCATION
- ☐ INTEGRATION
- ☐ CHARACTER
- ☐ INTEREST/EXCITEMENT. (ATMOSPHERE)

Figure 6. Disused mine shafts 'The problem' and 'Design principles'.



CRITERIA TO GRILLE A MINE SHAFT FOR BAT USAGE.

☐ GRILLS SHOULD BE PLACED AT, OR OVER THE ENTRANCE TO MINIMISE DISTURBANCE TO AIRFLOW – (NOT AT THE NARROWEST POINT)

☐ THE DESIGN SHOULD ALWAYS INCLUDE A DOOR AT LEAST 500mm SQUARE (ACCESS FOR FUTURE SURVEY WORK)

☐ INCASE OF VANDALISM, THE LOCK SHOULD BE THE WEAK LINK SO THAT IT BREAKS FIRST RATHER THAN THE GRILLE.

☐ RECOMMENDED BAR SPACING FOR LARGE BATS (IE THE GREATER HORSE-SHOE BAT) IS 750mm APART WITH 150mm SPACING BETWEEN THEM

☐ HIGH TENSILE REINFORCING STEEL 25mm IN DIAMETER IS RECOMMENDED.

REQUIREMENTS

1. BAT ACCESS

* THE MINIMUM SPACING REQUIREMENT FOR THE GREATER HORSESHOE BAT, IS 750mm × 190mm.

☐ BATS REQUIRE A VERTICAL STACK OF HORIZONTAL BARS AT THE CORRECT SPACING (SEE ABOVE)

2. ENTRANCE

BATS REQUIRE HORIZONTAL ACCESS INTO SHAFTS, THEY THEN SPIRAL DOWNWARDS. THE SHAFT GUARD THEREFORE MAY BE ABOVE GROUND LEVEL.

3. ☐ TEMPERATURE
☐ HUMIDITY
☐ AIR FLOW

THESE NEED TO REMAIN CONSTANT IF THE BATS ARE TO CONTINUE THEIR ROOSTS – ELSE THEY WILL LEAVE FOR AN ALTERNATIVE LOCATION

4. FOOD SUPPLY – BATS FEED ON INSECTS, WHICH LIVE IN WOODLANDS, HEDGEROWS AND PASTURES ETC. IF THESE HABITATS ARE REMOVED OR REDUCED IN AREA, THEN THERE ARE LESS INSECTS FOR THE BATS TO FEED ON. SIMILARLY THE USE OF PESTICIDES AND HERBICIDES REDUCE INSECT NUMBERS AND THUS BAT NUMBERS. THEREFORE NATURAL VEGETATION AROUND THE SHAFT AREA SHOULD REMAIN AS INTACT AS POSSIBLE

5. TOPOGRAPHY – SURROUNDING TOPOGRAPHY EVEN SUBTLE CHANGES CAN AFFECT THE AIR FLOW THROUGH A SITE – AND THUS AIR CURRENTS IN SHAFTS AND ADITS. A WALL OR MOUND AT AN ENTRANCE WILL TRAP A POCKET OF COLD AIR IN THE TUNNEL, WHILST DOMES OR AN OVERHANGING ROOF WILL PROVIDE WARMER AREAS.

DESIGN REQUIREMENTS FOR BATS.

CRITERIA TO ALLOW ACCESS TO CAVERS

☐ THE EXISTING MINE SHAFT SHOULD BE STABLE ENOUGH TO ALLOW SAFE ACCESS, PARTICULARLY AT THE SHAFT LINING OR 'GINGING'

☐ ACCESS DOWN THE SHAFTS SHOULD BE LIMITED TO THE CAVERS ONLY AND FOR SAFETY REASONS, OMIT THE PUBLIC

☐ TO ENSURE PUBLIC SAFETY WHILST MAINTAINING CAVER ACCESS THE OPENING SHOULD BE LOCKABLE

☐ A REFERENCE NUMBER, OR ANNOTATION OF THE SHAFT IS DESIRABLE FOR LOCATION, AND REFERENCE PURPOSES

REQUIREMENTS.

1. SIZE

ALTHOUGH THERE ARE NO SPECIFIC REQUIREMENTS OR RECOMMENDATIONS, THE SMALLEST AND LARGEST RANGE OF DIMENSIONS IS SHOWN BELOW:-

THE SMALLEST OPENING WOULD PRESENT DIFFICULTIES FOR SOME CAVERS, AND IS ONLY USED WHERE EXISTING CONDITIONS LIMIT LARGER OPENINGS

THIS IS THE MOST SUITABLE OPENING SIZE WHICH PERMITS SAFE AND EASY ACCESS WHILST IT IS OF PRACTICAL DIMENSIONS, AND IS USEFUL FOR BOTH HORIZONTAL AND VERTICAL OPENINGS.

2. FIXING.

TO HELP ACCESS DOWN SHAFTS THE PROVISION OF AN EYE BOLT OR OTHER TIE IS RECOMMENDED FOR TYING ROPES ONTO.

LID/COVER TO BE FIXED TO FRAME TO PREVENT REMOVAL BUT FACILITATE EASY ACCESS.

3. ACCESS

TO ALLOW EASY ACCESS DOWN THE SHAFT THE FOLLOWING CONSIDERATIONS ARE APPROPRIATE:

☐ THE REMOVABLE GRILL/COVER SHOULD HAVE A CHAIN OR WIRE ATTACHED TO PREVENT IT BEING TAKEN AWAY FROM THE SHAFT VICINITY.

☐ THE COVER SHOULD BE EASILY REPLACEABLE WHEN DAMAGED OR REMOVED FROM SITE.

☐ THE AREA AROUND THE SURFACE OF THE SHAFT SHOULD ALLOW SUITABLE 'GEAR' ASSEMBLY SPACE.

DESIGN REQUIREMENTS FOR CAVERS.

Figure 7. Disused mine shafts 'Design requirements for bats' and 'Design requirements for cavers'.

metalliferous mining as its major theme, and if funds permit, a major outdoor mining museum.

Phase 1 engineering works were completed in 1988 at a cost of £600,000. Planting of the reclaimed area is in hand in the winter of 1988/89. Phase 2 engineering works estimated to cost in excess of£1,000,00 will be carried on in 1989 with final planting to follow. Both grass and trees will be maintained for 3 years as part of the reclamation scheme, funded by the Welsh Development Agency, and will then become the responsibility of the Borough Council. Final figures on the costs involved in accommodating the special interests of the preservationists and conservationists will probably not exceed 4% of the cost of works, £65,000. The cost of providing advice over and above engineering and landscape design, costing about 8%, is a further 1%, £16,000.

Conclusion

It is important that abandoned metalliferous sites are reclaimedsince they can create serious environmental problems, however competing interests can make the task of reclamation difficult. A multi-disciplinary approach, careful reseach and a clear indication of the likely level of afteruse can produce a worhwhile and sometimes exciting result for a modest increase in cost.

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ASBESTOS TAILINGS RECLAMATION IN SOUTHERN AFRICA[1]

by

JJP van Wyk[2]

Abstract. The Institute for Reclamation Ecology of the University of Potchefstroom in South Africa started with research on Asbestos tailings and waste materials in 1982. The major findings were: that the natural angles of repose of tailings and waste materials of Crocidolite, Amosite and Chrysotile were too steep for rehabilitation (reclamation) and should be flattened to 18-20°. That all fibre containing material should be covered with course (gravelly) shrouding material to a depth of 300 mm. That storm water should be prevented from running over the treated surfaces to prevent erosion by means of berms and perimeter walls and toe paddocks should be constructed on USLE principels to reduce run off speed on slopes and contain rainwater falling on the treated areas on the dumps and in the adjacent toe paddocks. (USLE = Universal Soil Loss Equation).

Revegetation should be in accordance with general climatic conditions, surrounding vegetation type, and land use. Species used should preferably be selected from the local area; and where grazing and access trampling can not be controlled, unpalatable, impenetrable, (preferably non burnable) species with no economic use should be selected to discourage the presence of humans and animals.

Chemical and physical amelioration of tailings is necessary for Chrysotile because of the high Magnesium content, other mineral imbalances and cementing of the surface. Normal fertilization is sufficient for Crocidolite and Amosite.

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Introduction

The objective of the rehabilitation programme is to eliminate the pollution sources and prevent fibre from becoming air born or distributed by water, humans and or animals, by the implementation of research results.

There are three major asbestos producing regions in Southern Africa i.e. The Northwestern Cape Province, Central Northern Transvaal and the Eastern Transvaal (figure 1).

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[1] Paper presented at the 1989 joint conference of the Canadian Land Reclamation Association and American Society for surface Mining and Reclamation, Calgary, Alberta, August 27-31, 1989.

[2] Jacobus J P van Wyk (Prof.) Director Institute for Reclamation Ecology, Potchefstroom University, Potchefstroom, 2520, South Africa.

Due to vast differences in climatic conditions, topography, soils, vegetation and land use between the regions/localities, different strategies are employed in the different regions/localities as will be discussed in this paper.

Due to the high cost of earth works and large variation with regards to pollution potential amongst tailings and waste materials, the pollution potential of each fibre containing locality is assessed to determine priorities to decide on the chronological order to rehabilitate in the region/area.

Assessment of Pollution Potential on a score point basis

Localities, tailings and waste materials, are classified (ranked) according to their physical nature from high pollution potential to low pollution potential as 1. Millsites; 2. Cobbing dumps/sites; 3. Waste material with high fibre content; 4. Waste materials with low fibre content.

Secondary sources such as roads, loading/unloading spots, floodplains, agricultural lands (where asbestos was used as soil conditioner or simply dumped), dwellings (built or plastered with asbestos mud and/or cow dung without the use of cement) are also scored according to the circumstances.

Geographical and Topographical configuration

Tailings and other pollution potential localities are ranked with regards to their relative position inside, partially inside, very close to or distant from: 1. Big rivers or water courses; 2. Big tributaries and 3. Small tributaries.

Topographic position (average water speed and flood lines) is super imposed on the geographical position to place a "value" on the pollution potential.

Inherant erosion potential with regards to water, wind, trampling and subsiding (surface sliding)

Surface stability varies from place to place for a number of reasons. Factors such as fibre length, amount of coarse material on the surface, trampling, chemical reactions and cementation by especially Chrysotile, are evaluated for ranking purposes.

General Rainfall Conditions

Weather records are being studied to assess average, and maximum rainfall and excessive heavy downpours to determine flood frequency (200 year floodline) and current and past floodlines.

General wind conditions (direction and speed)

Exposure to wind and general prevailing wind directions is determined from weather station data, and polluted areas are classified and ranked based on their wind pollution potential.

Population Density

The population density and distribution of farms, villages, towns and cities is carefully mapped and scored in conjunction with wind conditions and pollution spreading by means of water (Geographic, Topographic configuration).

Ownership

Ownership is determined where the owner can be identified. Defunct mines and/or closed mines where there is no owner any more, becomes the responsibility of the Government.

Other factors

Various other factors are being assessed to finally round off the determination of priorities. They include such aspects as:

- Condition of access roads

- Accessibility to humans and animals
- Availability of shrouding material
- Availability of accommodation, water and other commodities
- Natural veld types, the condition thereof and land use.

Once all these conditions and/or factors and/or circumstances has been assessed, and ranked (scored) a final figure can be ascribed to each pollution locality indicating its priority for rehabilitation amongst its neighbours (figure 2).

After the chronological order of priorities has been determined, and the applicable strategy for the various priority localities been agreed on, surveys are carried out to determine existing profiles and calculate volumes to be moved (removed). At this point earth moving contractors are invited to tender, or are appointed on a price per volume basis, under the supervision of this Institute.

Establishment of vegetation

Successful establishment of vegetation has been achieved in all three major asbestos mining regions mentioned in figure 1.

Species selection and establishment techniques were all based on basic and applied research findings carried out for at least three years in greenhouses (on campus) and locally in field trials, before rehabilitation was started.

Research

The research entails the following:

Surveys and Species selection. Local botanical survey at each locality with a pollution potential (Mining site, tailings, waste rock, etc.)

Identification of suitable species to be used for rehabilitation. For various reasons, but especially to prevent excessive trampling and over grazing, which would enhance future erosion, species with the following properties are selected for areas where grazing can not be controlled:

- No, or very low grazing potential (caustic)
- Fire resistant or quick recovery after fire
- Low growing and impenetrable (creepy and spiny)
- Adapted to grow on Asbestos tailings and waste materials containing fibre
- Drought resistant and self maintaining (no aftercare)
- Species with no economic importance to human beings such as wood or edible fruit.

In areas where grazing can be controlled, mainly local grasses and "new ecotypes" of Eragrostis curvula, suitable for the particular climatic conditions and growth medium are selected for grassland regions. Local shrubs and trees are also established in Savannah and Woodland areas.

Establishment trials from vegetative material/seedlings/adult plants. Once the suitable species have been identified, seed and other reproductive material are collected and grown in tailings and fibre from each region in rootgrowth boxes with glass front panels in greenhouse experiments and on the tailings in the various regions.

Root development, phenology and vitality is carefully monitored for at least three consecutive seasons.

Shrouded Crocidolite and Amosite were found to be suitable to carry and maintain vegetation where as Chrysotile had to be chemically and physically ameliorated to establish an acceptable vegetation cover as is mentioned in the paper on Chrysotile reclamation.

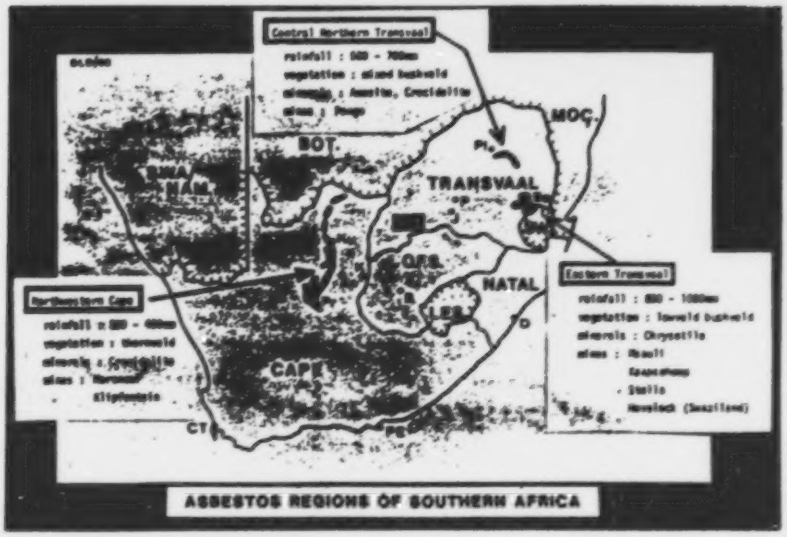
Central Northern Transvaal
vegetation : mixed bushveld
minerals : Amosite, Crocidolite
MOÇ.
BOT.
SWA
NAM
TRANSVAAL
O.F.S.
NATAL
LES.
D
CAPE
CT
PE
Northwestern Cape
vegetation : thornveld
minerals : Crocidolite
Klipfontein
Eastern Transvaal
vegetation : lowveld bushveld
minerals : Chrysotile
Havelock (Swaziland)
ASBESTOS REGIONS OF SOUTHERN AFRICA

Figure 1.

Asbestos producing regions in South Africa and Swaziland. Crocidalite is mined in the Northwestern Cape, Amosite and Crodidalite in the Central Northern Transvaal and Chrysotile in the Eastern Transvaal and Swaziland.

Figure 2.

A Chrysotile polluted valley in the Eastern Transvaal. The tailings in the centre foreground are filled in over the banks of a large tributary of the Komati (a major) river. The big distant dump is on the banks of the Kamati river, but fortunately above the flood line.

Chemical analyses of the tailings of Chrysotile indicated imbalances of heavy metals and very high Magnesium contents of up to 2 000 ppm.

This led to a number of chrysotile tailings amelioration experiments as is discussed in the Chrysotile paper.

Establishment trails from seed and cuttings. The majority of species selected for asbestos tailings (and waste) rehabilitation has not been cultivated before. Therefore an investigation was concurrently undertaken with establishment trails from seed and cuttings to determine the intricacies of establishment of the selected species from seed and/or cuttings.

Field trials

Field trials are normally started during the second season and are based on the results of the greenhouse experiments of the first season.

They include the establishment of the selected species from transplants from the local vicinity, establishment by means of seedlings and/or cuttings and establishment from seed.

Micro habitat climate manipulation such as the placing of rocks around the seeding points, shading of seeding points, creating depressions at seeding points, etc. forms part of the exercise.

Species performance in pure and mixed stands is also carefully monitored during various stages of development and through consecutive seasons.

Implementation of revegetation

Once the research has reached the point that the results can be implemented, and enough vegetative material, seed or cuttings are on hand, surfaces where the earth works has been completed are revegetated with suitable species for the particular environmental configuration.

Implementation strategies (a few representative examples)

The case studies represent rehabilitation procedures, carried out initially with limited funding in the early stages to adequate funding, currently.

Malips river, Central Northern Transvaal

In this case the tailings could not be removed from the river bed as the continuous dumping over approximately 30 years caused the river to gradually widen to the opposite side of the fill - thus changing is course. The tailings currently does not interfere with the current flow as the new channel has widened and deepened to allow two meter high by 60 meter wide floods before reaching the base of the tailings (figure 3).

There was also no suitable place to dump the tailings, when removed from the original part of the riverbed, and also no suitable shrouding material in the vicinity.

As all the dwellings and gardens of the mining town were earlier demolished, (to prevent people from living amongst un rehabilitated dumps) stone for cladding was in abundance available.

It was therefore decided to flatten the river facing slope to 18 - 20^{0}, construct a foundation two meters wide, starting down on bedrock and building it up to 2 - 3 metres above the river bed.

The flattened tailings was shaped level with the top of the foundation wall, stone cladded (stone pitched) and sealed with a cement-sand mixture.

A perimeter wall was constructed at the top end of the stone pitched area to allow water from the rest of the dump to run into the river after being filtered through specially constructed stone filter walls.

Storm water from the adjacent mountain was channeled sideways before reaching the tailings.

Rabe's Kloof Large Tributary (Central Northern Transvaal)

In this case the tailings were dumped inside and on one bank of the large tributary of the Malips river over a distance of roughly one kilometer. The height of the tailings varied from 20 to 70 metres (figure 4).

The side on which the tailings were dumped was generally wide enough to allow for the removal of all the tailings from the bed and "contaminated" bank and mountainside and also to leave "clean" space of 20 metres for the construction of the toe dams, adjacent to the stream. The rest of the tailings was flattened to 18 - 20^0 except for one locality where mill tailings and waste rock were mixed. Due to space limitation and the high rock contents this area (10 % of the total) could only be flattened to 25 - 30^0. The total area was shrouded with clean, course gravelly alluvial material. The highest portion of the tailings stretches about 250 metres up the side of the mountain.

During construction a cloud burst of 10 inches (250 mm) of rain within three hours occurred, and caused the stream to totally overflow its banks with some damage to the earth works in progress.

It was decided to widen the streambed to three times its original dimentions. Due to the fact that the newly created bank between the tailings and the stream consisted of loose allavial material it was decided to build a foundation, anchored in bedrock where possible at the base of the wall with a one metre high wall on top of it. The bank was shaped to join the top of the wall. The total surface of the bank is currently being stone cladded and sealed with a cement-sand mixture. The cement mixture is coloured with oxide to blend with the brown colour of the cladding stone. Gutters are being provided to allow runoff from the rehabilitated surface to enter the stream under controlled circumstances.

Due to the altitude difference of ± 250 metres between the top and bottom, horizontal stone walls were constructed at 20 metre intervals to reduce the speed of the surface runoff water.

Berms were constructed around the top perimeter of the rehabilitated area to prevent runoff from the rest of the mountain from reaching the rehabilitated surface.

Revegetation was done by hand, using cuttings and seed of selected species with the characteristic's mentioned earlier. (A species list is provided later in this paper.)

Schegters Kloof Small tributary (Central Northern Transvaal)

The tributary was filled with tailings over a distance of 200 metres to an average height of 3 - 4 metres (Figure 5).

The mountain sides on both sides of the stream consisted of deep "clean" alluvial material.

The tailings could easily be removed from the streambed and burried on both sides of the stream.

Stone walls were packed in the stream bed at 25 - 54 metre intervals. Berms were constructed around the upper perimeter of the rehabilitated area to prevent runoff from higher terrain reaching the rehabilitated area.

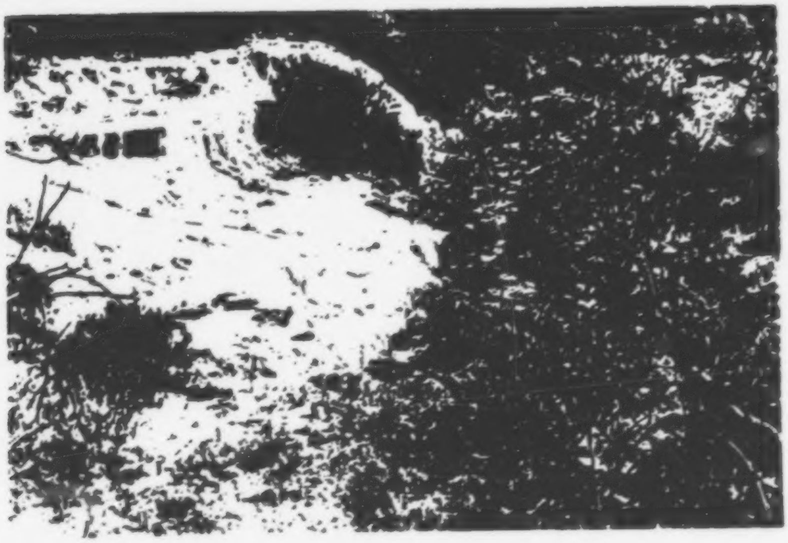

Figure 3.

A situation similar to the Malips river where tailings was dumped on the bank and over the bank into the streambed of the river.

Figure 4.

Rabes Kloof site in the process of rehabilitation. Tailings has been removed from the streambed, flattened to 18-20°, shrouded and planted with selected species. Stone pitching is in progress.

The species used in all three cases are the following:

Acacia hebeclada
(spinescent, low spreading shrub)
Acacia schweinfurthii
(spinescent scrambling shrub)
Aloe davyana
(succulent with low palatability)
Aloe immaculata
(succulent with low palatability)
Aloe longibracteata
(succulent with low palatability)
Aloe mutans
(succulent with low palatability)
Euphorbia cooperi
(caustic spinescent unpalatable succulent)
Euphorbia ingens
(caustic spinescent unpalatable succulent)
Sanseviera aethiopica
(fibrous unpalatable succulent forming clumps)
Sanseviera hyacinthoides
(fibrous unpalatable succulent forming clumps)
Senecio longiflorus
(fibrous unpalatable succulent forming clumps)

Floodplain Geminy Central Northern Transvaal

This project is in its exploration stage due to the fact that local inhabitants live and farm (under irrigation) on the contaminated flood plain. The long narrow plain is about 60 hectares in size (1 ha = 100 x 100 metres) and rises 1 - 4 metres above the normal water level of the river.

According to the local farmers the plain, or part of it, floods bi-annually (figure 6).

The depth of the tailings on top of the surface varies from 0,5 - 4 metres on dwelling sites, and from 300 mm to ploughing depth below the surface in the agricultural lands. Most of the tailings have been dumped during mining operations and the rest has deliberately been spread by the farmers as a soil conditioner.

As soon as the inhabitants can be convinced by ther local Goverment and Chief to temporarily evacuate the area, the rehabilitation will begin by means of removal of slimes where it has been dumped on the surface and not ploughed into the soil.

The rest (80 %) of the area will be cleaned up by means of a mini open cast mining operation where the contaminated soil and surface tailings will be buried and clean soil from the sub surface will be brought to the surface and spread over the contaminated buried material.

The area will be contoured to prevent erosion in case of future flooding.

The existing canal irrigation system will be improved, re-designed and constructed.

Conclusion

This Institute has sucessfully rehabilitated asbestos dumps since 1986 and has now been asked to estimate the total cost for a National Clean up of Asbestos pollution in the Republic of South Africa and Swaziland (figure 7).

Although all the mining sites are well known and documented, the extent of secondary contamination surfaces surrounding those areas, has never received attention.

It is questimated at this point in time that a national clean up could cost between R250 - R300 million rand.

The current asbestos mining companies also use this Institute as consultant and rehabilitation is ongoing on a large scale.

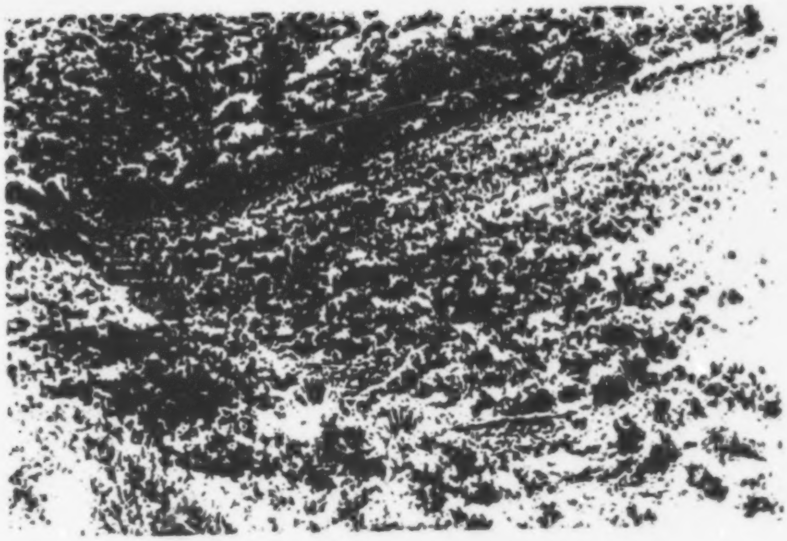

Figure 5.

Schegters Kloof after rehabilitation. The treeless portion indicate the rehabilitated surface. Note the stone walls in the streambed.

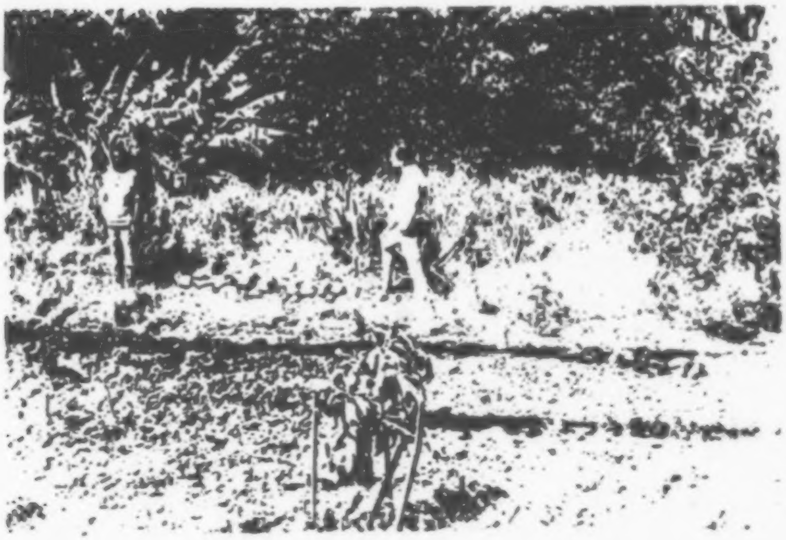

Figure 6.

Fruit and vegatable farming on the Gemeni floodplain.

Reference

Van Wyk, J.J.P. and Dawson, B.L. 1985. Proceedings Environmental Workshop. Vol. 1. p.387-392. Australian Mining Industry Council, Darwin. ISBN 0909276250.

Figure 7.

A Rehabilitated tailings dam two seasons old. Note the natural veld with big trees in the back and branch fence to keep animals out during establishment.

MINE TAILINGS RECLAMATION IN AUSTRALIA - AN OVERVIEW[1]

by

L.C. Bell[2], S.C. Ward[3], E.D. Kabav[4] and C.J. Jones[5]

Abstract. The paper briefly reviews legislative requirements for rehabilitation of mine tailings in Australia before consideration of case studies of rehabilitation in bauxite, base metal, gold and uranium mining operations. For particular mineral industries, comparisons are made of the limitations and approaches to tailings rehabilitation in markedly different geographic regions.

Introduction

Mining and mineral processing makes a major contribution to the Australian economy and, in 1987/88, exports of minerals and primary mineral products were valued at A$17,819 million representing 44% of the country's merchandise exports. Most of this production was derived from the 264 mines extracting metallic materials (primarily bauxite, gold, iron ore, copper, lead, zinc, nickel and uranium ores) and the 121 mines producing coal. The distribution of the major mining and mineral processing operations in Australia is shown in Fig. 1.

Most of the mines producing metallic minerals and their associated mineral processing plants produce tailings which must be contained to prevent on-site and off-site pollution during the mine life and which must be subsequently rehabilitated such that the disposal site has long term stability against the erosive forces of wind and water. Tailings dams are also a common feature of the coal mining industry. The fine particle size coal tailings have the potential to be retreated to produce a marketable product, and thus few dams have been rehabilitated with a vegetative cover to a condition where they could be abandoned.

The objective of this paper is to briefly review the rehabilitation of tailings resulting from mining and mineral processing in Australia. Some general comments about the legislative requirements for rehabilitation will be made prior to a discussion of some case examples for a number of the major mining industries where tailings rehabilitation is a major concern (bauxite, base metals, gold and uranium).

Legislative Requirements

Most of the specific legislation related to environmental matters including tailings containment and rehabilitation in Australia has been produced by the individual State Governments as a result of the division of powers under the Australian Constitution. The Commonwealth Government does have the opportunity to ensure that mining proposals are environmentally sound, however, through the Environment Protection (Impact of Proposals) Act of 1974 which requires that an environmental impact statement be prepared for projects proposed by or on behalf of the Commonwealth. Where export of minerals is involved, the Commonwealth Government has the power to prevent export where the environmental impact of the proposed operation is adverse. In addition to this non-specific power, the Commonwealth

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[1] Paper presented at the 1989 symposium jointly sponsored by the Canadian Land Reclamation Association and the American Society for Surface Mining and Reclamation, Calgary, Alberta, August 27-31, 1989.

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Government does have the power to legislate with respect to specific details of environmental control of mining for territories such as the Australian Capital Territory, the Australian Antartic Territory and, to a lesser extent, the Northern Territory (uranium) (Australian Environmental Council 1984).

At a State level, the legislative requirements with respect to air and water quality around tailings dam during filling, and to rehabilitation requirements once the dam is full, vary considerably from State to State. Even for a given State, the stringency of requirement may vary depending on the age of the mining operation; some old mines operate with requirements to protect the air and water quality of the mine surrounds but have no requirement for rehabilitation of tailings dams. Most new mines have legislative requirements covering rehabilitation and may involve specific reference to covering of the tailings with soil and establishment of a self-sustaining vegetative cover.

Bauxite Residue Tailings

In Australia, bauxite is mined in the northern tropics at Weipa (Comalco Aluminium Ltd.) and Gove (Nabalco Pty. Ltd.). In the temperate south-west, bauxite is mined at Jarrahdale, Huntly, Del Park and Willowdale (Alcoa of Australia Ltd.) and Mt. Saddleback (Worsley Alumina Pty. Ltd.). The bauxite mined at Weipa is beneficiated and then shipped to Gladstone on the central Queensland coast for refining (Fig. 1). There is a refinery at Gove, while in the south-west, Alcoa of Australia has refineries at Kwinana, Pinjarra and Wagerup, and Worsley Alumina has a refinery at Worsley near Collie. These six refineries produce 36% of the western world's alumina. Comalco Aluminium Ltd. operated a refinery at Bell Bay in Tasmania between 1956 and 1972.

All these refineries use the Bayer process and generate significant quantities of alkaline residue (2.7 mt/a of residue from the two northern refineries and around

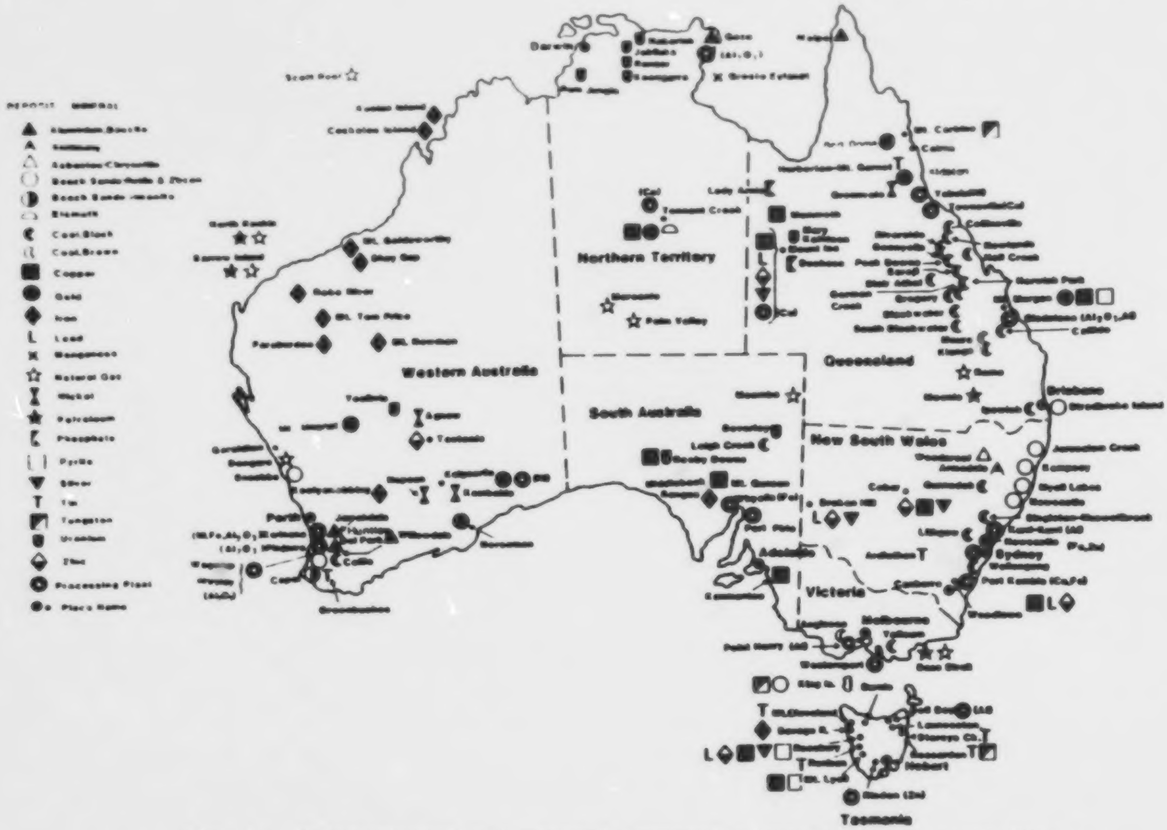
Darwin
Gove
Weipa
Northern Territory
Western Australia
Queensland
South Australia
New South Wales
Victoria
Tasmania
Perth
Collie
Adelaide
Brisbane
Sydney
Melbourne
Hobart
Cobar
Copper
Gold
Iron
Lead
Natural Gas
Petroleum
Uranium
Zinc
Processing Plant

Fig. 1. Major mineral and mineral processing operations in Australia.

12 mt/a at the four south-western refineries). In the Bayer process, alumina is extracted from bauxite by digesting the crushed ore in sodium hydroxide at elevated temperature and pressure. The solid residue from the refining process is often separated into two size fractions during refining, viz. the coarse fraction known as residue sand (>150 µm) and a fine fraction known as red mud (<150 µm).

Properties of the Tailings

Red mud consists primarily of iron, aluminium and silica minerals, the dominant minerals being quartz, haematite and goethite. Alkaline substances such as sodium aluminium silicates (desilication product) are formed during the Bayer process and also form part of the red mud. Residue sand consists primarily of quartz with iron oxides such as haematite and goethite. The red mud fraction of the bauxite residues is dominated by silt and clay particles, whereas the residual sand contains little or none of these sized particles. The available water capacities of the mud and sand are moderately high and low respectively.

Most of the caustic soda associated with the residue is removed by washing, but a solution of sodium hydroxide, carbonate and aluminate remains entrained with the solids. At Gladstone, the bauxite residue is slurried in seawater after washing. At Gove, the residue is slurried with return liquor from the residue disposal areas, and at the other refineries fresh water is used. The tailings materials are all extremely alkaline, saline and sodic, and, when freshly produced, are incapable of supporting plant growth. In addition, both the red mud and sand are extremely deficient in nitrogen and phosphorus and, in many cases, the availability of manganese and zinc is also low.

Method of Tailings Disposal

Bauxite residue in Australia is usually disposed of by pumping it as a wet-slurry of 15-25% solids into natural depressions or lined or unlined artificial impoundments. 'Dry disposal' of residue has recently been introduced into a number of the refineries.

At Gladstone, red mud and residue sand are pumped to separate unlined ponds in a slurry of seawater. At Gove, a red mud/residue sand slurry is pumped to unlined containment ponds. At Bell Bay all the residue generated by the refinery between 1956 and 1972 is contained in an unlined 40 ha pond where it was depositied as a conventional wet slurry.

At Alcoa's refineries at Kwinana and Pinjarra, disposal was originally of a mixture of both red mud and residue sand. Since 1982, mud/sand separation plants have been operating at the disposal areas at these sites, and the two fractions can now be disposed of separately. At Wagerup, the two fractions have always been disposed of separately.

Alcoa's impoundments are up to 160 ha in area and around 20m deep with the total area of tailings at its three refineries now exceeding 720 ha. Leakage of caustic is prevented by a clay seal and, in one case, a synthetic membrane provides an additional seal. All impoundments built since 1983 have gravity underdrains to aid residue consolidation, improve caustic recovery and reduce the potential for leakage.

Approximately 50% of the red mud at Kwinana and Pinjarra is currently being disposed of by dry disposal which involves separating the mud and sand fractions using cyclones. The red mud is then dewatered to about 50% solids then pumped into an impoundment and solar-dried to around 70%-75% solids, at which time it has a strength similar to naturally occurring soils. The sand fraction of the residue is used to build dykes and to top-off filled disposal areas before they are reclaimed. The impoundments originally designed for wet-slurry disposal are being converted to dry disposal after appropriate drainage. Worsley Alumina Ltd. uses a dry disposal technique which involves dewatering. A combined red mud/red sand mixture is dewatered to about 55%-65% solids and then pumped into clay-sealed and underdrained storage areas developed in natural valleys adjacent to the refinery, where it is solar-dried.

Rehabilitation of Tailings

Plants are grown on or around residue disposal areas to control dust on operating areas, to prevent wind and water erosion on filled areas, to blend the areas in with their surroundings, to reclaim filled areas to a productive use and to stabilise the batters of the dykes surrounding the impoundments. Red mud, which contains the majority of the caustic solids such as the desilication product, is more alkaline, saline and sodic than residue sand. Red muds and residue sands slurried in seawater are more saline than those that are slurried with fresh water. Both materials are deficient in many of the nutrients essential for plant growth.

Before satisfactory plant growth can occur in both red mud and residue sand, their alkalinity, salinity and sodicity must be reduced. Meecham and Bell (1977), working with Gladstone refinery wastes, showed that the excess salts in residue sand could be quickly leached. Experience at Alcoa's refineries has shown that well-drained residue sand, which has a high hydraulic conductivity, can support plant growth after only a few weeks leaching by winter rainfall or irrigation, provided adequate plant nutrients are supplied. The red mud has a very low hydraulic conductivity, is not readily leached and remains very difficult to vegetate.

Tropical and sub-tropical sites. At Gove (12°S) much of the annual rainfall of 1800 mm falls between December and March, and there is a distinct dry winter season. The ability to survive this severe dry season is a major factor in determining a species suitability for growing on residue areas. Temperatures are high all year round, the average maximum ranging from 25°C in July to more than 30°C in December.

Ninety eight hectares of residue ponds have been rehabilitated at Gove. A further 85 ha of ponds have been filled, and there is currently one 170 ha pond being filled. These ponds are unlined but are built on a relatively impermeable material.

The main aim of rehabilitation is to establish a vegetation cover which stabilises the surface of the storage areas and eventually blends in with the surrounding flora. Salt - and alkali-tolerant grasses including Chloris gayana and Cynodon dactylon, legumes such as Stylosanthes humilis and Dolichos lablab, and tree and shrub species such as Eucalyptus alba, Acacia leptocarpa and Acacia holosericea have been established after covering the surface of impoundments with 10 cm of topsoil (Hinz and Doettling 1979). Growth and root penetration of plants has been greater on areas of sandy residue than on areas with finer residue (Hinz 1982).

At Gladstone (24°S), where Weipa bauxite is refined, the average annual rainfall is 972 mm, 60% of which falls from December to March. August and September are relatively dry, but the dry winter season is less severe than at Gove. The average daily maximum temperature ranges from 22°C in June to 30°C in January.

The main aim of vegetating the red mud and sand residue storage areas at Gladstone is to stabilise the surface to reduce wind and water erosion. Following extensive experimentation on the red mud tailings, Bell and Meecham (1978) concluded that, in the short-term, there was no prospect of vegetating red mud areas without using a minimum of 200 mm of soil to cover the surface. Growth limiting factors of the mud were identified as excessive salinity, alkalinity and sodicity as well as severe deficiencies of nitrogen, phosphorus, manganese and possibly zinc. A major factor identified for successful rehabilitation was the provision of drainage to prevent upward movement of salt.

The current rehabilitation technique involves building bunds around the area to be rehabilitated, allowing the red mud to drain and then covering the mud with 200 mm of topsoil. Superphosphate, ammonium sulphate and zinc sulphate fertilizers are applied and the area sown with Chloris gayana, Cynodon dactylon and Macroptilium atropurpureum. Acacias native to the area have colonised the rehabilitated areas within three years.

The residue sand at Gladstone is disposed separately from the red mud in bunded low lying areas. Bell and Meecham (1977) showed that establishment of vegetation on this material could be achieved by leaching of excess salt and addition of fertilizer; incorporation of fly ash from the refinery's power station significantly improved the sand's ability to support plant growth through the increase in available water of the mixture.

Mediterranean sites in south-west Australia. The south-west corner of Western Australia has a mediterranean climate with a wet mild winter and a hot dry summer. The average annual rainfall ranges from 858 mm at Kwinana to 1050 mm at Wagerup (Fig. 1). This rainfall is reliable but seasonal, with about 80% falling between May and September. Annual gross evaporation is high generally being in excess of 2000 mm. The mean maximum daily temperature in July is around 17°C and the minimum 9°C. In January the mean maximum daily temperature is around 30°C and the minimum around 18°C.

Of the three Alcoa refineries, that at Kwinana has 298 ha of tailings of which 93 ha have been rehabilitated, that at Pinjarra has 381 ha of which 10 ha has been vegetated, and the Wagerup refinery has 42 ha all of which is still being used for disposal. The Worsley Alumina Ltd. refinery has not yet filled any of its disposal areas.

At Alcoa's refineries, it has been found that the most important requirement for successfully establishing vegetation on residue disposal areas is to ensure that the surface is covered by a well-drained layer of residue sand; it is extremely difficult to grow plants on areas of exposed red mud. Areas filled prior to 1973 at Kwinana, the oldest refinery, presented problems for rehabilitation as the edge-of-empoundment disposal resulted in a separation of the sand and red mud leaving the central areas of the ponds difficult to vegetate. Subsequently sand areas were pushed from the fringes to the centre of the ponds and/or sandy topsoil applied to the central areas. These procedures, plus the installation of surface drains, allowed vegetation to be established successfully. In impoundments built since 1973, dumping points have been rotated so that large-scale separation of red mud and residue sand does not occur. Also, the mud/sand separation facilities at the disposal areas enables hydraulic placement of a layer of sand (1 m) over mud areas following some surface strength development by drainage and drying.

Alkaline groundwater in the filled impoundments at Kwinana is removed using pumps, and the alkali recovered is re-used in the refinery. Controlling the perched groundwater by combination of pumping and surface drains prevents capillary rise of salts which can be a major factor restricting successful rehabilitation. Bottom drains, included in impoundments built since 1983, will increase the recovery of caustic and reduce the level of groundwater in the impoundments when they are filled.

Rehabilitation of the Alcoa refinery wastes has always concentrated on agricultural use of the areas as they are surrounded by predominantly farming areas. The current rehabilitation procedure is to establish a vegetative cover in the first instance to control dust. On filled impoundments, this initial cover may be replaced in subsequent years with a range of possible crops. Ideally, rehabilitation is timed so that autumn rainfall can leach the sand of entrained alkali before sowing. After surface preparation, which includes incorporation of 120 m^3/ha of organic matter, the areas are seeded to S. cereale and L. rigidum. Legumes such as Medicago polymorpha and Medicago sativa may also be sown. In summer, a layer of rock mulch is laid down after sowing to control dust before the plants become established. Finally superphosphate with copper and zinc and ammonium nitrate are applied. Potassium, magnesium, manganese and boron have also been applied to some areas.

The pasture species which have shown the most promise for grazing and hay production in the years following the initial reclamation with S. cereale and L. rigidum are the Medicago polymorpha varieties Serena and Circle Valley, Trifolium balansae and Trifolium fragiferum var. Palestine. A wide range of vegetables have been grown successfully on filled impoundments.

A number of species of native trees and shrubs have been planted on or have invaded the filled areas at Kwinana. The most successful species are Eucalyptus camaldulensis, E. platypus, Casuarina obesa and Melaleuca armillaris. Other species which are surviving and growing include Jacksonia sp., Acacia saligna, A. cyclops, Eucalyptus gomphocephala, E. coolibah, E. botryoides, E. rudis, E. cladocalyx, Melaleuca lanceolata and Casuarina glauca. However, excavation of the root systems of some of these trees has shown that root development is restricted to areas of residue sand or imported sandy topsoil.

The control of dust is important in the efficient management of operating disposal areas and bitumen or paper mulches, rock mulching, irrigation, establishment of a vegetation cover and the use of mesh windbreaks have all been used. Irrigation and growing a cover of vegetation have proved the most successful dust control methods.

Another solution to the problems of managing bauxite residue areas is to find uses for the material. Incorporation of gypsum-treated red mud into coarse sandy soils on the Swan Coastal Plain has been shown to increase pasture yields by up to

100% on well-drained sites due primarily to an increase in their water-holding capacity (Ward 1986). Amending these sandy soils with red mud has the additional benefit of reducing the amount of phosphorus fertilizer leached from them into adjacent coastal water-bodies. However, at the present time the costs associated with these alternative uses makes them uneconomic.

Conclusion

The management of bauxite residues in Australia has progressed considerably since the industry commenced in the 1950s. Some of the improvements which have been made in storage technology include the advent of 'dry' disposal, red mud/residue sand separation and under-drained storage areas. Improved dust control and a better understanding of how to grow plants on filled disposal areas have also been significant factors in improving the management of bauxite residues.

Base Metal Mine Tailings

In this paper, base metals are considered to include copper, zinc and lead which commonly occur as sulphide ores. Typically base metal operations involve extraction of the ore from the ground, grinding of the ore and separation of the metal sulphides from the remainder (80 to 99%) of the finely ground material which is disposed of in surface storages as tailings.

In Australia, base metals are mined at a number of locations (Fig. 1), but the two major mining areas for these metals are situated in semi-arid to arid areas around Mt. Isa in Queensland and Broken Hill in New South Wales. This section of the paper will review the rehabilitation of tailings at these two locations. Additionally, a brief discussion of the rehabilitation of tailings at a former base metal mine at Captains Flat, near Canberra in a sub-humid climate will be given as a comparison with the mines situated in a drier environment.

Broken Hill and Mt. Isa Mines

Broken Hill has been the site of mining and milling activity by a number of companies since the 1880s, the city developing around the mine operation and tailings disposal areas. This case study will discuss work carried out at The Zinc Corporation Limited and New Broken Hill Consolidated Limited (ZC/NBHC) which mine lead, zinc and silver from sulphide ores. At Mt. Isa, where copper, lead, zinc and silver sulphide ores occur, Mount Isa Mines Limited (MIM) began mining, milling and smelting operations in 1931. Tailings disposal areas lie to the west of the mine workings and the city.

Methods of tailings disposal and tailings properties. At both Broken Hill and Mt. Isa, tailings are hydrocycloned to separate the sand fraction (which is used as underground fill) from the silt and clay size fines. The fine tailings are thickened to 45 to 50% solids and pumped or gravitated to tailings dams.

The tailings dams at Broken Hill are constructed by the ring embankment containment method. Mullock forms the base of the first embankment which incorporates a road base and the starter bank with a coarse sand filter forming a drainage blanket. The dam is completed with a series of 10 m lifts of free standing walls built of tailings sand using the upstream method. The fine tailings are confined within these walls (Kelly and Lean 1983; Chilman and Johns 1978). Thus, on completion of the dam, there are two distinct areas for treatment; the unstabilised portion of the sloping embankment made up of coarse tailings and the horizontal top surface of the dam composed of the fine slime fraction. Harris and Leigh (1976) characterise the properties of each area as follows. Wall material has a high permeability to water and air and is easily penetrated by plant roots; metal sulphide and soluble salt content is comparatively low, although soluble salts can concentrate at the base of the wall from seepage and evaporation. Material on top of the dam has low permeability making plant root penetration difficult. Metal sulphide and soluble salt content are comparatively high with salts often migrating to the area from more permeable material. Lean et al. (1983) note that tailings are neutral to slightly alkaline as a result of the lack of active sulphide minerals and the use of alkaline conditions in the treatment of plants.

The valley containment method at Mount Isa currently uses a zoned earth and rockfill wall about 31 m high constructed across a narrow valley to enclose a catchment area of over 20 km^2. The final projected capacity of this dam (No.8) in 20 years is about 100×10^6 m^3 of tailings covering about 1400 ha (a number of smaller dams totalling 115 ha are no longer in use).

Tailings are discharged into the dam at a point furtherest from the embankment forming a gently sloping beach with gradients ranging from about 1 in 75 to 1 in 850. No provision is made for stormwater diversion from the valley catchment; however, the high evaporation rate and some re-use control the water level. A small quantity of seepage from the embankment is returned to the pond.

As the Mount Isa embankment acts as a water holding dam, unassisted drying of the tailings mass is slow. High evaporation rates result in the net upward movement of moisture and dissolved salts producing a substantial salt crust on the tailings surface. As the dam catchment extends beyond the tailings surface, rainfall runoff is concentrated onto the tailings.

The properties of the Mt. Isa tailings relevant to the rehabilitation have been reviewed by Bell and Jones (1987). Approximately 90% of the solids discharged to the storage area are less than 37 mm in diameter. The material lacks aggregation and forms a massive structure with high bulk density and surface crust strength. Infiltration of water is very low, but available water is reasonable.

The dominant minerals in the tailings are quartz and dolomite with smaller amounts of muscovite, orthoclose, albite, limonite, gypsum, pyrite and traces of the metal-containing minerals chalcopyrite, galena and sphalerite. Generation of acid from oxidation of pyrite is neutralized by the dolomite, and the pH is kept approximately neutral. The level of soluble salts is extremely high, and the material is very deficient in nitrogen and phosphorus.

Rehabilitation of Broken Hill tailings. The major objectives of rehabilitation of the tailings are to control wind erosion and to improve the visual impact because of the dams' proximity to residential and commercial areas. Thus vegetation is the preferred stabilizing agent, but the major constraint to its establishment however, is the arid climate. The annual evaporation of 2000 mm far exceeds the very low annul rainfall of 224 mm, most of which falls in winter. Mean maximum temperature in December, the hottest month, is 31°C, whereas the mean minimum temperature in July, the coldest month, is 5°C.

Some work was initiated in the mid 1950s to counteract problems of wind-blown dust from the sides and tops of the elevated tailings dams (Harris and Leigh 1976; Lean et al. 1983). However, it was not until the 1970s that the availability of the trickle irrigation technique and a supply of sewage effluent water from the Broken Hill treatment system allowed large scale rehabilitation tests using vegetation on the sides of the dams (Thorne and Hore-Lacy 1979; Lean et al. 1983). The sewage water has a relatively high salt content, but contains sufficient nitrogen, phosphorus and potassium to supply the needs of the wide range of native species used in the rehabilitation program.

Of the 30 species planted as seedlings in autumn, Eucalyptus camaldulensis, E. largiflorens, Acacia salicina, Tamarix parviflora, Atriplex nummularia and Pinus halepensis are the most important. The plants are watered by a combination of drip then sprinkler irrigation for approximately 3 years in order to ensure their survival (Lean et al. 1983).

Rehabilitation of Mt. Isa tailings. Research into rehabilitation of tailings dams began at Mount Isa in the 1960s. The objective was to develop and trial suitable techniques on small completed dams to control wind blown dust and improve their appearance, and apply successful approaches to the current operating No. 8 dam on its completion. Most of the research, which has been reviewed by Bell and Jones (1987), was carried out on the No. 3 dam of which about 30 ha has been rehabilitated.

As in the case of Broken Hill, climate is a major limitation to the establishment of a stabilizing vegetative cover at Mt. Isa (chemical methods of stabilization proved unsuccessful). The area has a semi-arid climate with an annual rainfall of 429 mm and annual evaporation of 3117 mm; evaporation exceeds rainfall in each month of the year. Summer temperatures are high with the mean maximum temperatures exceeding 36°C in each of November, December and January. In winter, frosts are rare, and the lowest mean monthly minimum temperature of 12°C occurs in July.

Early research showed that the major limitations to plant growth on the Mt. Isa tailings were excessive salinity, low levels of nitrogen and phosphorus and high bulk density, combined with the arid climate (Hunter and Whiteman 1975). Glasshouse and field trials showed that leaching of salts with irrigation and application of nitrogen and phosphorus fertilizer would enable growth of some pasture species to be achieved. Mixing of fly ash, a waste product from the local power station, with the tailings in 1:1 ratio to a depth of 20 cm greatly improved plant growth through an improvement in physical properties. Leaching of salts was increased by the improved infiltration; the available water capacity was also improved. The ash had no major detrimental chemical properties and had the additional advantage of having moderate levels of available phosphorus.

Of the grass species tried, those giving the best growth were Rhodes (Chloris gayana), buffel grass (Cenchrus ciliaris) and couch (Cynodon dactylon). Although these results were encouraging, the maintenance of nutrient levels and the water requirements were demanding, and this approach was not seen as a long term solution to revegetation of the dams. Subsequently trials were established to assess the suitability of using crushed rock as part or all of the root zone in the tailings rehabilitation. A siltstone is mined and used to fill underground voids, and this operation produces a large amount of <50 mm waste which was available for use on the tailings dams. The material is dominated by quartz, dolomite, muscovite, albite and orthoclose. Apart from its deficiency in nitrogen and phosphorus, it has few chemical limitations to plant growth, although its available water capacity is low.

Initially the siltstone was applied as a 70 mm layer on the tailings and either left undisturbed or incorporated into the tailings. Application of fertilizer and irrigation produced good growth of Rhodes grass particularly in the surface-applied treatment. The major advantages of the surface-applied stone mulch were (1) the stones provided protection to the emerging seedlings by reducing wind erosion and sand blasting, (2) the salinity of the tailings immediately below the rock decreased due to better water infiltration and (3) evaporation and upward movement of salt was also reduced.

In spite of the fact that a relatively thin layer of siltstone mulch resulted in reasonable establishment and persistence of introduced species such as Rhodes grass, additional trials by MIM staff showed that it was necessary to apply up to 1 m of siltstone on the tailings surface to support the heavy equipment used to dump and spread the material. An advantage of such a thick layer of relatively coarse material is that it acts to reduce upward migration of salt by capillary rise. The most recent rehabilitation has involved the incorporation of 100 mm of fly ash into the top 1 m of siltstone to improve water holding capacity.

In the initial rehabilitation trials, emphasis was placed on the use of grasses which would build up organic matter in the tailings surface to produce a more favourable environment for subsequent plantings or invasion of native species. In 1980/81, approximately 30 ha of an old tailings dam, which had been treated with an 0.3 to 1.0 m rock layer and a surface incorporation of 100 mm of fly ash, was planted to introduced grasses (Rhodes and buffel) and a large number of native shrub and tree seedlings which are now dominated by Aerva javanica, Acacia hemsleyi, A. holosericea, Atalaya hemiglauca and Eucalyptus argillacea. The vegetation was supplied with trickle irrigation for 2 years to ensure the survival of the majority of the seedlings. Monitoring of this area will provide valuable information on the long term stability of the system which can then be used in the rehabilitation of the remaining tailings areas (> 1500 ha) when they become available in approximately 20 years.

Captains Flat Mine

Captains Flat is a former zinc, lead, copper, gold and pyrite mining area about 50 km upstream from the national capital, Canberra, on the Molongolo River (Fig. 1). Mining, which started in 1874 and continued periodically until 1962, involved extraction of the minerals by froth flotation and subsequent disposal of the tailings. Hydrocycloning was used to separate the tailings into a fine fraction which was pumped to earth dam storage areas, and a coarse fraction which was piled high to form large dumps. At the cessation of mining, the total area covered by fine and coarse tailings was 15 ha (Craze 1979).

The tailings dumps were unsightly and a major source of air and water pollution. The dumps of fine and coarse material lacked stability along their outer faces and, in 1939 and 1945, two dumps collapsed into the Molongolo River, and the material covered alluvial flats, 15 km downstream, with polluted material. In spite of efforts in 1961 and 1962 to prevent further collapse of the dumps by application of slag or tar to the dam walls, the treatments were unsuccessful, and considerable pollution of the Molongolo River continued. A joint State and Federal Government committee was formed in 1974 (Anon 1974) to enquire into the problem of pollution from Captains Flat and to recommend procedures which would lead to a permanent abatement of pollution of the Molongolo River.

In contrast to Mt. Isa, Captains Flat has a temperate climate and a moderate rainfall of 740 mm/a which is distributed relatively evenly throughout the year. In summer, pastures and crops experience periods of moisture stress. Mean monthly temperatures range from 20°C in summer to 6°C in winter when frosts are frequent; the growing season is constrained by the fact that there are only 85 frost-free days per year.

The tailings at Captains Flat contained a range of sulphides which, on oxidation, resulted in pH values less than 3. High salinity and high concentrations of zinc, lead and copper prevented any plant growth on the tailings, and the acidity, salinity and metal load in the mine drainage escaping to the Molongolo River effectively sterilized it for many kilometers downstream.

Research by Craze (1977) showed that plant growth on tailings limed to an acceptable pH with 40-50 t/ha and fertilized with nitrogen and phosphorus was still poor as a result of other limiting factors such as salinity. There was also no guarantee that the pH would stay in a favourable range because of the large amount of sulphate on the tailings. In order to achieve the objectives of stabilizing the tailings against erosion and leaching, therefore, it was apparent that the tailings would have to be recontoured and covered with a medium which was capable of supporting plant growth. The tailings were reshaped to produce terraced slopes with grades not greater than 33% and not less than 5%. These slopes were chosen to reduce erosion, to facilitate revegetation and to provide adequate surface and internal drainage. The terraced slopes were then covered with approximately 220 mm of compacted clay to seal the tailings from air and moisture to reduce oxidation of the sulphides. On top of the clay seal was placed 450 mm of shale rock to inhibit capillary rise of any toxic water which might move through the clay from the tailings and to provide a lateral drainage layer. Finally, a 300 mm layer of the surface of a nearby soil was placed on the rock fill to enable establishment of a vegetative cover.

Considerable laboratory, glasshouse and field testing of the final procedure used was undertaken by the Soil Conservation Service of New South Wales (Craze 1979). A grass-legume pasture was established on the fertilized and limed soil by sowing a mixture of _Agrostis tenuis_, _Festuca arundinacea_, _Cynodon dactylon_, _Vicia dasycarpa_, _Trifolium pratense_ and _T. repens_. _Secale cereale_ was also included in the mixture as a quick growing cover crop. After planting, the surface was covered with a straw mulch and bitumen and watered by sprinkler irrigation. The pasture is maintained by the periodic application of fertilizer and the slashing of the pasture.

Only time will tell if the rehabilitation program, which cost approximately A$3.5 million, will be successful in the long term. Craze (1979) indicated, however, that, in 1979, the revegetated areas appeared to be stable to significant storm events and that the pollution in the Molongolo River was dropping; the pH of the river water had risen from 4.1 to 6.5, the metal content had declined dramatically, and algae had begun to reappear.

The pollution problem arising from mining at Captains Flat developed at a time when there were few environmental controls on mining. Current legislation should preclude such examples as Captains Flat ever occurring again in Australia.

Gold Mine Tailings

Gold has been mined in Australia since the 1850s when the country produced almost 40% of the world's production. Production of the metal has fluctuated markedly since that era with the industry currently undergoing a major resurgence, particularly in Western Australia and Queensland. In Western Australia, the largest producer, the major goldfield is centred on Kalgoorlie-Boulder (Fig. 1) where the metal has been mined for about 90 years. In Queensland the resource is more dispersed, and a large number of small mines operate down the eastern portion of the state. Many of these mines are new with little rehabilitation of tailings being undertaken, and thus this paper will concentrate on the goldfields of Western Australia.

Gold mining in the arid Kalgoorlie-Boulder area has resulted in the production of approximately 500 ha of tailings dumps which flank the twin towns. The dumps are particularly vulnerable to wind erosion and have been identified as the major source of dust in the area. The tailings have been contained by a ring embankment system using coarse tailings to raise the life of the embankment. Such an approach has produced solid tailings structures with outside face slopes up to 70° and heights of 40 m (Kurzeme 1986).

The particle size of the tailings varies with the age of the dump, the older deposits having a coarser texture. However, all deposits are dominated by the fine sand fraction (53 to 74%), which is particularly prone to movement by saltation and effective in sand blasting of seedlings (Nunn 1981). The available water capacity of the tailings is moderate, but little water is held in the air dry state and cohesion between particles of the dry tailings is poor. Chemical analyses indicate the tailings are alkaline (8.3 to 8.7) and that salinity in the top 150 mm can range from moderate to high with a tendency for the salt concentration to be highest in the surface 20 mm.

The climate is a major limitation to vegetative stabilization of the tailings dam with a mean annual rainfall of 238 mm which is winter dominant. The evaporation is 2436 mm per annum and exceeds rainfall in each month of the year. The mean maximum monthly temperatures range from 16.5°C in July to 33.6°C in January, whereas mean minimum monthly values range from 4.8°C in July to 25.9°C in January.

Early attempts to stabilize the tailings dumps by vegetation were not successful, and thus non-vegetative measures were tried (Marshall et al. 1978). Trials showed that 40 mm screened rock fragments at a rate of 40 t/ha significantly reduced wind speed at the surface and particle movement by 80 to 90%. Unfortunately the effectiveness of the treatment declined rapidly after 2 years. Additional research showed that a rate of 124 t/ha of rock fragments was necessary for long term effects but that this rate was uneconomic. Subsequently heavy black granular waste (iron silicate) from the Kalgoorlie nickel smelter was applied as a 9 mm thick blanket (200 t/ha) over the tailings following wind tunnel experiments which showed it would have long-term effectiveness in stabilizing the tailings. This material, which is provided free of charge by the smelter, is now an integral part of the rehabilitation program involving vegetative stabilization.

In the early 1980s, renewed emphasis was placed on trying to use vegetation to stabilize the tailings dumps at Kalgoorlie, and considerable success has now been achieved following trials which identified appropriate native species and documented the need for phosphorus and micronutrients (Burnside et al. 1986). The recommended procedure now involves (1) establishing low contour banks (200 mm high and 3 to 5 m apart) to reduce wind velocity and increase water availability to the plants, (2) direct seeding of saltbush species such as *Atriplex nummularia*, *A. undulata* and *A. amnicola*, (3) application of phosphorus, copper, zinc and molybdenum fertilizer and (4) addition of at least 200 t/ha of nickel smelter slag as a surface mulch (approximately 10 mm). Only a small proportion of the 500 ha of dumps have been treated in this manner. There is the possibility that some of the older tailings dumps will be reworked for gold, but it appears that techniques are now available to achieve rehabilitation on those not destined for disturbance in the near future.

Uranium Mine Tailings

Australia has large reserves of uranium with significant deposits in the Northern Territory, South Australia and Western Australia, but most mining to date has been confined to the Northern Territory (Fig. 1). In the 1950s and 1960s, a number of uranium mines in the Northern Territory operated by mining companies on behalf of the Commonwealth Government. Most of these initial mines had ceased operation by the early 1970s and, as no legislation requiring rehabilitation of the mines existed at the time, the mining works, mill facilities and tailings dumps were abandoned at the end of operations (Bastias 1987). Relatively new mines were established at Narbarlek in 1979 and Jabiru in 1980, under strict Commonwealth Government environmental legislation, but the stage of operation of these mines has not yet allowed rehabilitation of tailings.

The climate of area containing uranium mines in the Northern Territory is monsoonal with a mean annual rainfall of 1500 mm, most of which falls in the period from November to March. Much of the rain falls during storms and intensities are high creating the potential for excessive erosion on unprotected areas. The long dry season coupled with a high evaporation leads to water stress, and this influences the choice of plant species in rehabilitation programs.

The abandonment of uranium mines initially developed in the 1950s and 1960s in the Northern Territory resulted in several examples of major environmental insult (Bastias 1987; Ryan 1987). At Rockhole and Moline, tailings (2 ha and 18 ha respectively) were contained by bunds which later failed resulting in erosion and transport of tailings downstream. Analysis of the area affected by the tailings showed high levels of metals and an unacceptable level of radioactivity. The tailings have been found to contain economic concentrations of gold and, since 1985, a company has been given the authority to extract gold from this material at Rockhole and Moline. Environmental requirements of this new operation include the building of new tailings storage structures and the retrieval of tailings and contaminated soil downstream from the original tailings dams (Bastias 1987).

Another abandoned uranium mine, that at Rum Jungle in the Northern Territory (Fig. 1), was responsible for costliest rehabilitation program ever undertaken on an Australian mine (approximately A$20 m). Uranium and copper ore concentrates were produced between 1954 and 1971 from five open-cuts in close proximity. After mine closure, no rehabilitation was required or undertaken (Ryan 1987). The mining and processing operations resulted in the pollution of the nearby East Finniss River with acid mine drainage resulting from oxidation of pyrite in the mine waste and overburden and causing elevated levels of aluminium, iron, copper, zinc, cobalt and manganese.

Between 1982 and 1986, the overburden heaps and tailings dam were rehabilitated, and the 4 million m^3 of acid water in pits treated. Tailings had been disposed onto 33 ha of bunded low lying land, and some of this material had been eroded into the adjacent East Finness River. The pollution resulting from the tailings was removed by excavating the material (approximately 330,000 m^3) and dumping into one of the existing open-cuts. The floor of the original tailings dam was treated with 8 t/ha of hydrated lime, covered with 300 mm of topsoil, fertilized and seeded to a mixture of tropical grasses (*Chloris gayana*, *Cynodon dactylon*, *Brachiaria decumbens*, *Urochloa mozambicensis* and *Paspalum notatum*), legumes (*Stylosanthes hamata* and *S. guianensis*) and native shrub and tree species (Acacias and Eucalypts). The former tailings area and rehabilitated overburden heaps are maintained by annual mowing and by application of fertilizers every second year (Ryan 1987).

The environmental planning and legislation which are associated with the new uranium mines in Australia should result in the avoidance of the pollution problems and high cost of after-thought rehabilitation which have been unfortunate features of the Rum Jungle mine.

Conclusions

This paper has briefly reviewed tailings rehabilitation for some of the major mining industries in Australia. It has not been possible to cover all mining operations in the country which have to dispose of tailings, but the examples given provide an insight into the range of limitations affecting rehabilitation and the approaches used to overcome them.

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TECHNIQUES FOR RECLAIMING METALLIFEROUS TAILINGS IN WALES[1]

by

John P. Palmer[2]

Abstract. Wales has a considerable legacy of abandoned metalliferous mine sites. These sites are often a landscape scar and pollution and public health hazard. Research into plant material tolerant of the high concentrations of metals found, covering systems preventing upward and downward migration of metals, public health aspects of metals in the environment and the movement of metals through ecosystems has provided a sound basis for land reclamation schemes. Adequately designed tailings movement, drainage, capping systems and vegetation cover and proper integration of these with land use are essential for successful reclamation schemes.

Additional Key Words: metal tolerance; covering systems

Introduction

Metal mining in the United Kingdom has been carried out since pre-Roman times. Production of metals has been subject to large fluctuations in demand even in the short term and many mines have been worked and reworked intermittently for centuries. The industrial revolution caused large numbers of metal mines to be opened up in the late seventeenth century and early eighteenth century but the great period of British metal production was between 1840 and 1890. After the decline in the 1890's many mines continued production until the early part of the twentieth century but very few remained operating after the 1940s. In 1989 there is one tin mine operating in Cornwall and intermittent gold production in very small quantities from mines in Wales.

The legacy of derelict land

The reclamation of metalliferous tailings in Wales is, therefore, a matter of reclaiming land at disused and abandoned mine sites. There has never been any reclamation of metalliferous spoil in Wales during the operation of a working mine and it has been estimated that there are 2000 ha of derelict land despoiled by metal mining and processing in Wales (Johnson et al 1977).

The techniques of ore treatment were such that there were never large tailings impoundments as we see at some modern mines but there were large tailings dumps and some mines did have small tailings dams.

Many of the problems associated with modern tailings are however found at these abandoned mines. Figure 1 illustrates a flowsheet of ore treatment at the Goginan lead mine in Mid-Wales in 1848. It can be seen that there are three major types of waste:

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- Coarse grained tailings
- Fine grained tailings
- Slime pit waste.

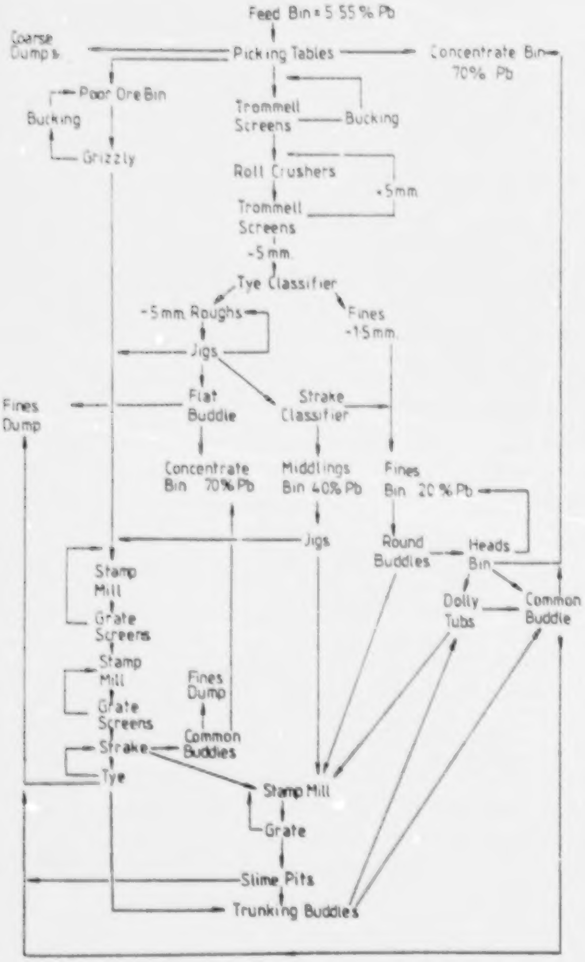
Feed Bin = 5.55% Pb
Coarse Dumps
Picking Tables
Concentrate Bin 70% Pb
Poor Ore Bin
Bucking
Grizzly
Trommell Screens
Bucking
Roll Crushers
+5mm
Trommell Screens
-5mm
Tye Classifier
-5mm Roughs
Fines -1.5mm
Jigs
Fines Dump
Flat Buddle
Strake Classifier
Concentrate Bin 70% Pb
Middlings Bin 40% Pb
Fines Bin 20% Pb
Jigs
Round Buddles
Heads Bin
Dolly Tubs
Common Buddle
Stamp Mill
Grate Screens
Stamp Mill
Grate Screens
Fines Dump
Common Buddles
Strake
Tye
Stamp Mill
Grate
Slime Pits
Trunking Buddles

Figure 1 A flowsheet of processes at the Goginan Mine Mill in 1848 (from Hughes 1988)

Many sites still have large quantities of these wastes. They commonly contain up to 2% of metal and sometimes considerably more. The fine wastes are a particular problem because:

- they often contain high concentrations of metal (see Table 1).
- the fineness of the waste means that a high proportion of the total metal content is often 'available'.
- when dry they are subject to wind blow.
- they are easily subject to water erosion.
- many are permanently wet and have thixotrophic properties and are very difficult to handle.

Table 1 Total Concentrations of some metals in mine tailings in Wales (ug g^{-1})

Site (metals mined)	Pb	Zn	Cd	Cu
Minera (Pb/Zn)	14000	34000	435	625
Y Fan (Pb/Zn)	42400	6700	268	376
Halkyn (Pb/Zn)	22882	65187	380	174
Parys Mountain (Cu)	63	88	nd	1390
Goginan (Pb)	175000*	9600	16	nd
Drws-y-Coed (Cu)	800	660	nd	37000*

* Maximum levels; nd - not done

All metal mining sites in Wales are near water courses because of the widespread use of water as a source of power in the mines and in the treatment processes. Some major rivers are polluted, particularly with zinc, because they run through mining districts or are fed by mine drainage. In addition large areas of land adjacent to mine sites may have become polluted by wind blow of toxic waste. On some sites wastes have been reprocessed - this activity was particularly common with respect to the removal of zinc from lead mining waste at the beginning of this century. Generally because of the long history of mining at many sites they are a complex of ruined buildings, spoil heaps and open shafts.

Reclamation of these abandoned mines therefore has one or all of three aims:

1. To reduce a risk to public health through contamination of air, water and soil.
2. To make the sites safe.
3. To clean-up rivers which are polluted from mining activities.
4. To remove landscape scars.

Because mines are old there are two considerations which have to be taken into account during reclamation which may not feature in reclamation of more recent tailings operations. These are:

- the industrial archaeological value of some of the remains
- the nature conservation value of plants growing on the wastes.

These are dealt with in Richards (1989).

Research into the reclamation of metalliferous tailings

Research in the UK into the reclamation of metalliferous tailings has concentrated on spoils in Wales and has focussed on the following areas:

1. The tolerance of plant material growing on metalliferous spoils to the metals found in the spoils.
2. The movement of metals from spoils into the ecosystem.
3. The relationships between heavymetals in the environment and public health.
4. The use of covering materials aimed at preventing upward migration of metal ions.

Plant material tolerant of heavy metals

Much work has been done on the nature and mechanism of metal tolerance in grasses found on metalliferous spoils in Wales (Smith

Table 2 Metal tolerant cultivars of grasses commercially available in the UK

Grass	Source	Comments
Festuca rubra cv. Merlin	Trelogan Mine, North Wales	Tolerant of lead and zinc. Although selected from a mine in an area of calcareous rocks this cultivar can also be apparently successfully used on more acid tailings.
Agrostis capillaris cv. Goginan	Goginan Mine, Mid-Wales	Tolerant of lead and zinc. Suitable for use on acid spoils.
Agrostis capillaris cv. Parys	Parys Mountain North Wales	Tolerant of copper and lead. Suitable for use on acid spoils.

and Bradshaw 1972, Powell et al 1986, Humphries and Bradshaw 1976, Johnson, et al 1977). Three grasses have been selected and produced commercially for use on metal spoils (Table 2). There are few instances of research into metal tolerance in trees on metalliferous spoils. This may in part be due to the almost ubiquitous grazing of mine sites by sheep in Wales. There are however some mine sites supporting trees. These are most commonly birch (Betula pubescens or B.pendula) and Willow (usually Salix caprea). Work by Brown and Wilkins (1958 a,b) has established that Birch from Cwmrheidol mine in Mid-Wales is more tolerant of zinc than that from control sites and that this tolerance may be assisted by mycorrhizal infection. Among the advantages suggested for the use of tolerant species are the following:

- The ability to vegetate spoils of high metal content without covering of a non-toxic material.
- Better binding of a non-toxic cover material to the underlying toxic spoil because the roots of a tolerant species will penetrate the underlying spoil.
- Lower herbage concentration of metals in tolerant plant material than in non-tolerant.

There have been very few instances where tolerant material has been sown directly onto spoil material in Wales. Tolerant material has however been used in many reclamation schemes in conjunction with a cover of non-toxic material.

The movement of metals through the ecosystem

These studies have included work on the metal content of invertebrate and vertebrate herbivores and carnivores on heavy metal sites (Coughtrey and Martin 1975, 1976, Roberts et al 1978, Roberts and Johnson 1978), the effect of heavy metals on aquatic ecosystems (McLean & Jones, 1975; Newton, 1944) and the effect of windblown dust on soil metal levels (Davies and White, 1981). This latter study provided the impetus for a reclamation scheme to control wind blown dust at Cwmsymlog in Mid-Wales.

Heavy metals in the environment and public health

Studies have been carried out in a metal mining district in Scotland and Wales to ascertain the extent to which blood levels are affected by heavy metals, particularly lead, in the environment. Anecdotal evidence from mining districts has suggested that lead in water supplies has caused brain damage to individuals in the past but the establishment of a relationship between lead in the environment and health in modern Britain has been less easy. Both water supply and household dust have been suggested as a principal route by which lead gets into the body (Elwood & Gallacher, 1983; Moffat, 1987). However in these studies in Wales and Scotland, in lead mining districts, blood lead levels were within EEC limits and lower than in some British cities. Work is currently being carried out on lead in dusts soils throughout Britain in order to assist the government to set acceptable standards for lead in soils and some initial survey work has been published (Culbard et al 1988).

The use of covering materials to prevent upward movement of metal ions

Relevant research on this topic has included field trials on metalliferous spoils in Wales using different capping materials, laboratory experiments simulating the field situation using columns of spoil, capping materials and break layers and specific research into the use of different types of break layers to prevent upward migration of metal ions (Jones et al 1982; Cairney 1987). Trials established by Liverpool University and the Robinson Jones Partnership Ltd in 1975 on lead/zinc spoil at Minera in Wales have been particularly informative in terms of the performance of the treatments used (Johnson et al 1977).

These trials were reviewed 12 years after their initiation in order to provide design criteria for the reclamation of lead/zinc wastes at Minera (Richards Moorehead and Laing Ltd 1988a).

Reclamation Techniques

The possible ways in which spoil contaminated by heavy metals can be reclaimed are:

1. By covering the waste in situ with uncontaminated material.
2. By excavation of the spoil and encapsulation in a previously prepared cell on site.
3. By amelioration of the wastes and vegetating them with metal tolerant plants.
4. By excavation of the spoil and removal off-site.
5. By on-site reprocessing of spoil to remove metals as a commercial exercise and incorporating restoration of the site.

Methods 1 to 3 have all been practised in Wales and 1 and 2 will be illustrated in the following case studies. Method 4 is rarely carried out because of the large quantities of material involved. Method 5 has been considered as an option at some sites in the UK (Richards Moorehead and Laing Ltd 1985) but has not recently been carried out successfully in Wales. There are sites however where substantial quantities of spoil exist and which could be reprocessed commercially. At one site the combination of reprocessing with a reclamation and development scheme is being given serious consideration.

Reprocessing as mean of reducing the 'contamination status' of a waste is not however as straightforward as might appear. The extent to which metal can be removed from spoil is dependent on the mineralogy of the spoil, the particle size of the feed material and the process used. Although much metal can be removed from a metal-rich spoil, for example reprocessing may extract 70% of the metal in a spoil containing 6% metal, the waste from the reprocessing activity may be no less contaminating. This is because its particle size may have been much reduced resulting in a much larger surface area and consequently greater availability of metal.

A study of the effectiveness of reclamation methods for contaminated land in Wales has recently been completed (Richards Moorehead and Laing Ltd (1988b). This included metalliferous mines reclamation. It concluded that a major reason for unsuccessful schemes was a failure to adequately predict the movement of water in the completed schemes. This resulted in continued pollution of water courses and contamination of capping materials.

The following case studies illustrate current approaches to metalliferous tailings reclamation in Wales.

Parc Mine

At Parc Mine there was a 2.2 ha complex of fine tailings dumps, slimes ponds and derelict buildings remaining from mining in an area of calcareous Ordovician shales.

The reclamation scheme at Parc was carried out because of erosion of tailings dumps and pollution of the adjacent watercourses Nant Gwydr and the Afon Conwy and its flood plain. It had been estimated that 13000 tonnes of material had been removed from the tips by sheet and gulley erosion since the abandonment of the mine. The scheme involved regrading the site, burying fine material and slimes under coarser materials capping the whole site with a 375 mm layer of quarry waste and sowing with metal tolerant cultivars of grasses. Particular attention was paid to site drainage. Monitoring of suspended lead and zinc soon after reclamation showed that their levels had been much reduced compared to the situation prior to the reclamation scheme being carried out. This was particularly so in flood situations. Monitoring of lead and zinc levels in the Nant Gwydr by the Welsh Water Authority since the site was reclaimed has shown that the water quality has not deteriorated since then. Water quality in the Nant Gwydr has however never been good because the stream has its source in an old mine adit. The levels of zinc and lead in the Nant Gwydr are thus above those in EEC directives for supporting fish and other aquatic life and at about the EEC limit for the watering of livestock.

The vegetated area has mostly been managed for sheep grazing and 10 years after establishment is in good condition considering it is growing on quarry waste.

Goginan

Goginan mine is in an area of predominantly acid rocks of Silurian age in Mid-Wales. Goginan mine was worked for lead and silver from Roman times until about 1890 and on abandonment was a complex of spoil heaps, slime pits, shafts, adits and buildings. During the 1960's and 70's large quantities of spoil were removed for hardcore and country rock was quarried and removed. The site was again abandoned in the mid 1970's and subject to illegal fly tipping. Investigation of the site prior to reclamation commenced in 1987 and involved the following:

1. Characterisation of all the materials on site.
2. Investigation of industrial archaeological features and areas of nature conservation value.
3. Investigation of shafts, adits, structures and drainage.

Soils and spoils on most of the site had levels of lead or zinc above 'background' levels. Lead levels in spoil on the site ranged from 200 ug g^{-1} to over 17%. Uncontaminated subsoil suitable for covering was encountered at a depth of 1.5 m on part of the site. The reclamation scheme involved the following:

1. Removal of the most contaminated tailings to a containment cell excavated on site. The cell was lined and sealed with a polythene membrane.

2. Contaminated soils and tailings not placed in the cell were reprofiled and limed prior to capping with a 300 mm deep layer of granular material and 200 mm of subsoil.

3. Seeding with a grazing mixture and re-establishment of hedgerows.

4. Provision of new site drainage incorporating a bed of limestone to maintain a high pH.

5. Retention of some areas of natural vegetation because of their nature conservation interest.

6. Capping of shafts and provision of grilles in mine entrances. Particular regard was given to making the requirements of bats, which in the UK are a protected species under the Wildlife and Countryside Act.

There was not enough break layer material or subsoil on site so a substantial quantity was imported.

Minera

Minera is in an area of carboniferous limestone rocks in North Wales and was an important lead mining and smelting site which ceased operations in 1914. Because the area is in limestone country the natural colonised vegetation of some of the abandoned wastes was of considerable importance and some mining areas are now protected as nature reserves. The reclamation scheme was divided into two phases because of its size. An investigation similar to that at Goginan was carried out and was supplemented by the experience gained from the 12 year long trial of capping materials referred to previously. A particular problem at this site was the large quantities of fine tailings material spilling down a slope into the River Clwyedog and low lying areas of wet slimes. The scheme involved the following work:

1. The complete removal of fine tailings and underlying contaminated soil from the slopes down to the river. Deposition of this material in a fill area over existing slimes.
2. Covering of the deposited spoil in the fill area with a polythene membrane and a minimum of 500 mm of imported colliery spoil. A greater depth of colliery spoil was used in tree planting areas.
3. Sowing of a low maintenance grass mixture directly into the colliery spoil.
4. Protection and in some cases transplanting of vegetation of nature conservation value.
5. Capping of shafts.
6. Provision of site drainage.

The removal of fine tailings from the slopes down to the river enabled pollution of the river from this source to be minimised and tree planting on the slopes to take place into original ground. The importation of colliery spoil was facilitated by the proximity of a colliery spoil heap itself in need of reclamation. The covering of the metalliferous spoil with colliery spoil obviated the need for a separate scheme to deal with this material.

Major industrial archaeological remains were found underneath tailings when these were being excavated. These were carefully preserved under the direction of an industrial archaeologist.

More details of this aspect are given in Richards (1989).

Because of the large quantities of toxic fine material which were to be moved during the scheme, six static dust monitoring stations were set up to run continuously during the construction period. Construction personnel were required to wear personel dust monitors periodically during their work.

All water draining off the site during the construction period was routed through treatment areas to settle out suspended material in the water.

Thousands of cuttings of willows were taken from trees growing on the metalliferous spoil prior to the reclamation work starting in order to provide material for subsequent planting during the scheme. In addition mature willows which would otherwise be lost during the scheme were lopped and placed in a holding area for re-use.

Conclusions

The experience in Wales of dealing with metalliferous tailings is applicable to similar areas of abandoned mining and also to existing or future operations. Abandonment of tailings dumps without reclamation in Wales has had the following consequences.

* Pollution of major water courses to the extent that they support an impoverished fauna and flora.

* A public health hazard through wind blown dust contaminated with heavy metals.

* Pollution of farmland and gardens by wind blown dust and run off from contaminated heaps.

The techniques used in Wales for dealing with these problems have centred on:

* covering and containing the contaminated waste using coarse material to restrict the movement of heavy metals from the waste into the covering material or surrounding soil.

* the use of plants tolerant of heavy metals for revegetation.

Lessons that have been learned during reclamation of tailings in Wales are:

- Movement of weathered tailings will expose unweathered and unleached material. Great care has to be taken that the reclamation scheme does not cause greater pollution of water courses than was the case before the scheme commenced.

- Tailings should therefore only be removed if this is necessary to achieve the goals of the reclamation scheme.

- Covering of spoil material and incorporation of a break layer or membrane as a capillary break is an effective way of reclaiming metalliferous tailings. Restrictions may have to be placed on after use, however, to ensure that the capillary break is not disturbed. Monitoring of sward and soil metal levels should be carried out if the sward is to be grazed.

- The correct design of the drainage of a reclaimed site is crucial. Water should be prevented from draining through metalliferous tailings wherever possible by appropriate land form design and the use of cut-off drainage.

- Limestone beds are useful to reduce the dissolved metal loading of drainage water in acid areas but are not always long-term solutions - the limestone may quickly become coated with insoluble reaction products which impair its ability to neutralise the water.

- The interface between covering material and metalliferous spoil should be above the expected water table at all times. Containment cells encapsulated in a membrane should not be placed below the water table.

- Coarse material such as colliery spoil is suitable as a capping layer but should be infertile at depth to discourage the roots of the sward penetrating the underlying spoil.

- Deep rooting woody vegetation should not be used on the capping layer unless this layer is deep enough for the underlying spoil not to be penetrated by roots.

- Choice of species to be sown should be made carefully. Metal tolerant species may not be appropriate for non-contaminated covering material because the advantage of such species binding capping layer and spoil together by rooting into it has to be balanced against such roots being a means by which heavy metals can be transported to the uncontaminated capping layer. Some metal tolerant ecotypes are anyway outcompeted by non-tolerant ecotypes in uncontaminated soils.

- Some sites are of industrial archaeological and nature conservation value - these factors should be taken into account at the earliest stages of the design.

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SERPENTINE TAILINGS RECLAMATION[1]

by

JJP van Wyk[2]

Abstract. The serpentine formations in the Pretoria/Johannesburg region contains virtually no chrysotile fibre but those in the Eastern Transvaal (see figure 1, Paper Asbestos Tailings) contains large amounts of chrysotile. The tailings of those mines are therefore basically serpentine residues.

This paper deals with the rehabilitation of a closed down serpentine mine near Johannesburg and current research on chrysotile, sertpentine tailings, in the Eastern Transvaal. In the near future the programme will be expanded to also include Swaziland.

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Introduction

This Institute is the ecological consultant for the Department of Transport and various other Government Departments such as Minerals and Energy, Health, Water Affairs, etc.

The more or less twenty years exposure as reclamation consultant for the Department of Transport exposed the Institute to reclamation problems on a national basis; i.e. through all kinds of climatic conditions from desserts to sub-tropic's, from winter rainfall areas to summer rainfall areas, and gave us exposure to most kinds of vegetation types, soil and geologic formations.

Due to this wide exposure of ecological problems concerning rehabilitation (reclamation) of disturbed areas, the Institute developed a specific approach, i.e. that each problem area must be individually assessed and treated according to its own peculiarities.

The Individualistic Approach

The main aspects of the individualistic approach are the following:

1. A study of the vegetation in the vicinity of the disturbed area to determine the role of each species in the community with special attention to their rehabilitation potential, which includes:
   - potential to invade bare areas;
   - drought resistance;
   - seed production, germination and establishment under poor conditions;
   - recovery after fire, etc.;
   - unpalatable, if desired, for asbestos mines.
   - palatable where grazing can be controlled and where erosion is not a high risk.
2. Collection of seed and/or vegetative reproduction material.
3. Collection of representative soil samples.

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4. Physical and chemical analyses of the soil samples.
5. Chemical and/or physical amelioration of the soil based on the analyses.
6. Pot experiments in greenhouse and outside.
7. Establishment trials on site and a monitor programme of these, preferably for three growing seasons.
8. Seed production of the selected species on one of our seven seed production farms if they are not yet represented in our collection.
9. Drawing up a rehabilitation programme.
10. Act as consultant during implementation or physically do the implementation if the client so desires.
11. Implementation is normally followed up by two years of monitoring and, if needed, a light maintenance programme.

Rehabilitation of the Honingklip Mine

This serpentine mine closed down during 1987 because of a very low amount of asbestos fibre in the serpentine.

The quarry is about 13 ha in extent with an average depth of 5 metres. The walls were left vertical and varied between solid rock and partially weathered material with a thin layer of top soil which varied from 100 mm to 300 mm in depth. The floor was also solid rock but had been cracked due to the blasting.

The two tailings dumps and unsold ore were dumped over a ± 10 ha area. The average height of the tailings varied between 10-35 metres.

Another ± 7 ha in the vicinity was covered with a layer of tailings material and served as soccer field, parking area, roads, etc.

The reclamation programme was started in August 1987 with greenhouse experiments to determine tailings and quarry floor abnormalities and rectification procedures. This was followed by earthworks to flatten the vertical rocky slopes of the quarry to 15-18° and a ripping programme to break up the floor of the quarry.

The sides of the fine tailings dump were flattened to ± 18°, and that of the coarser tailings to 25°, as it was more resistant to erosion.

The greenhouse experiments in the mean time showed that the serpentine can be chemically rectified to sustain plant life and it was decided not to import topsoil.

Substrate amelioration and fertilizer was applied as follows:
Fertilizer and gypsum quantities per ha:

1. 3000 kg/ha calsium oxide
2. 750 kg/ha potassium chloride
3. 400 kg/ha superphosphate
4. 4 tons of gypsum/ha
5. After establishment 200 kg/ha 2:3:4(22) was applied.

Paddocks were constructed around the tailings and low lying areas to prevent rainwater from leaving the polluted area or carrying tailings to the nearby river systems or adjacent farms.

Hydroseeding and the planting of trees started in November 1987 and was completed in January 1988.

The seed mixture used contained ± 20 selected grass species and several *Eragrostis curvula* ecotypes, tree and shrub species. About 25% of the grass seeds were harvested locally through suction methods from the plants and soil surface. The advantage of the suction method is, apart from local seeds that are adapted to the local soil and climatic conditions; it also provides organic material, micro-organisms and a small quantity of topsoil, which are very important elements in rock quarry reclamation programmes.

The rest of the seed represents pioneer grasses and climax grasses selected for similar conditions as the Honingklip mine, i.e. drought resistant, good seed producers, etc.

The trees and shrub species mainly represent those that grow on local rocky outcrops, and were established from seed and seedlings.

The following grass species were represented in the seedmix:

Digitaria eriantha	2 kg/ha
Cenchrus ciliaris	3 kg/ha
Anthephora pubescens	2 kg/ha
Chloris gayana	3 kg/ha
Cynodon dactylon	1 kg/ha
Setaria sphacelata	2 kg/ha
Eragrostis tef	1 kg/ha
Eragrostis curvula	1 kg/ha
(different ecotypes)	
Pioneer mixture including:	
Phynchelytrum repens,	10-12
Eleusine indica & others,	kg/ha
Enneapogon cenchroides,	
Chloris virgata	8 kg/ha
Total	33-35 kg/ha

The small deeper portion of the quarry is developed as a dam with islands and trees to attract bird life. The small lower lying part of the quarry will develope as a marsh and the rocky localities as habitats for small mammals and the rest would remain grassland (figure 1).

Final inspection took place on the 28th of January, 1988, at which time the release certificate from the Department of Minerals and Energy Affairs was handed over to the owner.

Revegetation on solid rock portions of the quarry

In order to rehabilitate the solid rock portions of the quarry, a project to investigate the use of plants which naturally grow on solid rock with very limited moisture and soil was started. These plants are the so-called resurrection plants. because they simply stop functioning when water is depleted, dry out and go into a type of hybernation until moisture is available again.

These plants have several very unique adaptations:

- They "invade" the soil "pillow" traces that forms around lichens and mosses from wind blown dust and/or soil particles in runoff water.
- They become dormant when they have depleted the moisture in the "pillow", their rootsystem on top of the rock surface gathers more wind-blown and washed down dust and soil particles (figure 2).
- It is known that they "resurrect" out of dormancy within a few hours after the next rain, and that they can survive droughts up to 8-10 years, while in hybernation..
- It is also on record that they can survive "artificial drought" (being left in a suitcase) for more than 20 years.
- The plants currently under investigation are:
  Myrothamnus flabellifolius (shrub)
  Coleochloa setifera
  Cyperus rupestris var. *rupestris* (both sedge like)
  Mariscus squarrosus
  Selagninella and mosses

Conclusion

The result of the rehabilitation was so successful that limited grazing was started within one year after establishment to prevent the stand to go moribund.

At present about 20 bird species, small vertabrates and three small game species have returned to the site. The island created in the dam and two large trees provided on the islands serves as a rest and sleeping place for birds, while several waterfowl species live permanently in the dam.

Rehabilitation of serpentine tailings at Msauli mine

Rehabilitation of serpentine tailings from chrysotile mining, is currently still in the research phase, but

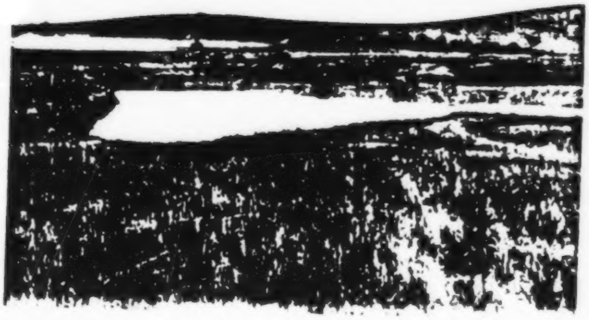

Figure 1. (A)

Good vegetation cover on tailings (foreground) and on quarry floor to the right of the dam and quarry sides flattend to ± 20° in the back.

Islands has been constructed in the dam and mature trees transplanted to attract bird life untill the planted trees mature.

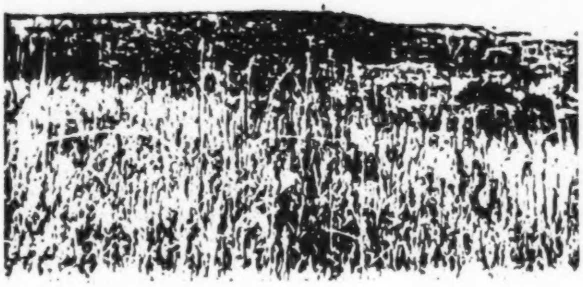

Figure 1. (B)

Vegetation cover on tailings dump and quarry floor.

Figure 2.

Myrothamnus flabellifolius lifted from solid rock. Note the soil pillow with all the roots confined to it. *Sellaginella sp* and *Mariscus squarrosus* are visible in foreground.

implementation will be started during the 1989/90 growing season.

Greenhouse experiments, based on physical and chemical analyses of tailings started during October 1984. The analyses revealed abnormalities in both physical and chemical properties. In all samples silt and clay particles were practically absent or very poorly represented. Magnesium was abnormally high, up to 2 000 ppm, with phosphate lower than 5 ppm. The pH of the slimes varied between 8,1 and 9,6.

Based on the results of the analysis, a pot experiment was designed in which various different soil treatments were included, as is indicated in Table 1. To lower the pH, three treatments of gypsum was used, i.e. 2,5 t/ha, 5 t/ha and 10 t/ha as is indicated in Table 1. Note that three levels of gypsum and three levels of potassium chloride were used along with the various amounts of organic material and soil moisturisers (water absorbing chemicals). The results varied but several tendencies were obvious. With the increase in gypsum application, the pH dropped from 8,8 to 7,6 and the number of seedlings that survived were somewhat higher than in the lower gypsum treatments. It is also evident from Table 1 that the vitality of the seedlings slightly increased with the higher gypsum application and that the application of organic material (compost) yielded slightly better results.

It must be mentioned that root development was generally poor and the vitality of the seedlings very low.

Due to the fact that no plants (not a single plant) naturally established on the various tailings dumps over a period of 30 years due to surface compaction and chemical abnormalities, it was decided to carry out a second set of pot experiments in which the surface and top 100 mm of the tailings was treated to change the physical and chemical properties. Larger amounts of organic materials and cow dung were used. Good results were obtained with higher applications of organic material and cow dung.

This was followed up by a field experiment. The lay-out, treatments and results are given in Table 2.

Seven plots of 11 x 11 metres in size were marked out (Table 2).
All seven plots received gypsum at 10 t/ha.
Numbers 2-6 received a 200 mm layer of coal ash (1 m^3 per plot).
Five plots received the same fertilizer mixture, except no 4 which did not receive potassium chloride, and number 6 which was not fertilized at all.
Plots 5, 6 and 7 received a 100 mm layer of cow dung (1,2 m^3 per plot).
Plot no 2 received the equivalent of 1,5 t/ha straw mulch.
The gypsum, ash, dung and mulch was mixed and worked into the top 250-300 mm slime, after which a 100 mm layer of topsoil was spread over all seven plots. The experimental area was fertilized and hand-sown. The following fertilizer and species were used:

NPK 2:3:2 (22) Zn	200 kg/ha
Superphosphate	500 kg/ha
Potassium chloride (KCl)	1500 kg/ha
Gypsum	10 t/ha

The seed mix consisted of the following:

Cynodon dactylon	3 kg/ha
Cenchrus ciliaris	5 kg/ha
Eragrostis curvula	2 kg/ha
Antephora pubescens	2 kg/ha
Panicum maximum	2 kg/ha
Digitaria eriantha	2 kg/ha

Aristida congesta	±60 kg/ha
Aristida congesta	
Aristida adscenciones	
Hyparrhenia hirta	
Hyparrhenia aucta	
Rhynchelytrum repens	
Enneapogon cenchoides	
Themeda triandra	

TABLE 1. VARIOUS SOIL TREATMENTS OF MSAULI MINE SERPENTINE TAILINGS

Gypsum application per ha	2,5 t/ha		5,0 t/ha		10,0 t/ha		Average of treatment	
	Average number of plants established	Average length of the tallest plant (mm)	Average number of plants established	Average length of the tallest plant (mm)	Average number of plants established	Average length of the tallest plant (mm)	Number of plants	Average height (mm)
Control	2,6	5,7						
Without potassium chloride (control)	7,2	12,8	11,0	20,2	8,8	15,2	9,0	16,0
+ 20 t compost	5,6	16,8	4,8	15,0	8,0	22,6	6,1	18,1
1000 kg potassium chloride (control)	5,6	6,8	6,2	11,2	12,0	15,2	7,9	11,1
+ 2 t gwanomix	11,6	12,4	6,4	9,6	11,6	16,6	9,9	12,9
+ 5 t gwanomix	7,8	11,4	9,6	14,8	8,4	16,0	8,6	14,1
+ 10 t compost	9,0	14,4	7,4	15,4	10,4	14,8	8,9	14,9
+ 20 t compost	7,4	14,6	10,2	20,2	10,2	16,8	9,3	17,2
+ 200 kg Aquastore	8,0	10,2	8,4	10,2	10,2	15,6	8,9	12,0
* + 200 kg Aquastore and * 200 kg Terrasorb	8,2	6,5	5,2	9,2	7,2	11,4	6,9	9,0
Total/average							8,6	13,8
2000 kg potassium chloride (control)	7,6	13,4	7,0	10,2	11,8	14,0	8,8	12,5
+ 2 t gwanomix	8,0	9,8	9,2	16,2	7,2	9,6	8,8	11,9
+ 5 t gwanomix	11,0	17,2	12,6	15,8	11,2	20,6	11,6	17,9
+ 10 t compost	6,8	9,0	7,6	10,0	8,4	18,0	7,6	12,3
+ 20 t compost	8,4	9,8	10,0	30,4	10,0	13,0	9,5	17,7
+ 200 kg Aquastore	4,0	7,4	6,4	7,8	8,8	14,4	6,4	9,9
+ 200 kg Aquastore and 200 kg Terrasorb	5,2	7,6	8,0	12,2	12,2	12,0	8,5	10,6
Total/average							8,6	13,3
Average for treatments	7,6	11,3	8,1	14,3	9,8	15,4		

* Aquastore and Terrasorb = soil moisture absorbents

TABLE 2. LAY-OUT, TREATMENTS AND RESULTS, 1988-89 SEASON

	1	2	3	4	5	6	7
	Gypsum	Gypsum	Gypsum	Gypsum	Gypsum	Gypsum	Gypsum
		200 mm ash	200 mm ash	200 mm ash	200 mm ash	200 mm ash	
		Mulch 1,5 t/ha			100 mm dung	100 mm dung	100 mm dung
	100 mm topsoil	100 mm topsoil	100 mm topsoil	100 mm topsoil	100 mm topsoil	100 mm topsoil	100 mm topsoil
	Fertilizer	Fertilizer	Fertilizer	No potassium chloride	Fertilizer		Fertilizer
A	16	17	22	23	29	29	27
B	1,0%	0,0%	0,5%	0,5%	5,5%	5,5%	4,5%
C	3,1%	0,0%	6,0%	6,0%	64,5%	56,8%	21,3%

A = Number of seedlings; B = Basal cover; C = Crown cover.

The results for number of species, basal and crown cover is clearly illustrated in Table 2. The results of plots 1-4 without cow dung are very poor in comparison with plots 5-7 which received cow dung (figures 3-4).

Conclusion

The inclusion of gypsum and organic material and cow dung is essential for the establishment of vegetation on chrysotile tailings.

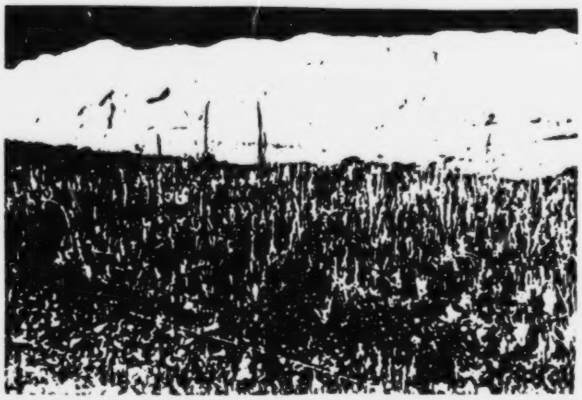

Figure 3.

The results of plots 5 and 6 four months after establishment.
Serpentine tailings behind the experiment is plantless.

Figure 4.

Species selection trails at Msauli.
Hyparrhenia hirta (taller grass) and Cynodon plectostachyus (Rhodesian star grass) are doing well two seasons after establishment

Appendices

PLENARY SESSION and GUEST SPEAKER

Procédures de réhabilitation: Activités d'exploration pour le pétrole et le gaz; Programmes d'assistance canadienne aux nations en développement

A. R. Scheibner

Le gouvernement du Canada avec la Corporation d'Assistance Internationale de Petro-Canada (P.C.I.A.C.) donne une assistance étrangère aux nations en voie de développement pour l'exploration des ressources pétrolières et gazières. Cette aide à l'étranger est donnée seulement qu'aux pays qui n'ont pas déjà une industrie de production de pétrole et de gaz.

Une politique mise de l'avant durant ces programmes d'exploration est le transfert de technologie par un entraînement approprié. Comme résultat du mandat du gouvernement canadien pour la protection globale de l'environnement une forte emphase à l'intérieur de cette politique est placée sur la protection environnementale et le transfert de technologie dans les domaines de planification et de surveillance environnementales dans les pays hôtes.

La méthode principale pour remplir ces objectifs est d'assurer une planification, une supervision et une surveillance nécessaires pour garantir que tous les contracteurs et le personnel canadiens vont mener le projet à terme selon une manière sécuritaire pour l'environnement. Les lignes directrices utilisées comme termes de référence sont généralement les règlements environnementaux des pays hôtes et ce qui est considéré comme de bonnes pratiques dans l'ouest canadien.

Ce texte présentera les procédures de planification et de terrain entreprises par le P.C.I.A.C. en fournissant la planification et la surveillance environnementale pour les projects sismiques et d'exploration au Ghana, à Madagascar, au Botswana et au Costa Rica. Le texte soulignera également les procédures de terrain entreprises par le "Western Oilfield Environmental Services Ltd." en travaillant avec les règlements environnementaux locaux et le développement de programmes de réhabilitation réussis.

Le travail entrepris avec les représentants des compagnie pétrolières et les ingénieurs des pays hôtes pour développer de meilleures procédures de construction et de réhabilitation sera également présenté dans ce texte.

Réhabilitation dans l'industrie sablière de l'Australie

Dennis R. Brooks

L'Australie est le producteur mondial majeur des produits de sablières. La responsabilité pour le contrôle des activités minières en Australie est confié à l'autorité des Etats quoique le gouvernement fédéral a promulgué une législation pour l'analyse environnementale des projets majeurs. Chacun des trois Etats impliqués, New South Wales, Queensland et Western Australia, ont développé des mécanismes différents de régulation. Cependant, en comparaison avec les mécanismes de régulation en Amérique, les procédures australiennes sont moins législatives et plus flexibles. Depuis que les activités minières ont commencée en 1934, l'industrie a extrait et réhabilité des terres variant des dunes de la côte à de vieilles dunes intérieures de plus de 100 mètres de haut. A l'exception de certaines terres agricoles au sud-ouest du Western Australia, la plupart des programmes de réhabilitation ont impliqué une végétation indigène et l'emphase a été donnée à la restauration d'écosystèmes fonctionnels. Les écosystèmes naturels restaurés incluaient des prairies et des arbustaies du littoral, des terres centrales, des forêts de bois dur, et une variété de terres humides. Les conditions climatiques rencontrées variaient de sub-tropical en passant par tempéré humide jusqu'à méditerranéen sec. Les principes pour réhabiliter les écosystèmes secs incluent la reconstruction de la forme du terrain, la gestion du sol de surface, la stabilisation des surfaces, l'établissement de végétation et la nutrition, et la surveillance du développment des sères végétales. La réhablitation des terres humides a des exigences supplémentaires incluant le contrôle des niveaux du sol et de l'eau, une gestion spécifique des exigences pour le sol de surface et une emphase sur le "timing" des opérations. Un certain nombre de sites réhabilités de sablières font maintenant partie des parcs nationaux.

Considérations sur la réhabilitation des terres aux Indes, en Afrique du Sud et en Espagne

Edward M. Watkin

La réhabilitation des terres perturbées par les activités industrielles ou de construction aux Indes, en Afrique du Sud et en Espagne nous fait voir différents contrastes entre ces pays.

En Espagne, la réhabilitation des terres est un concept relativement nouveau, imposé par la récente entrée du pays dans la Communauté Economique Européenne et le besoin de se conformer aux règlements environnementaux de la CEE. En conséquent, il y a actuellement très peu d'exemples de réhabilitation minière ou industrielle. Présentement, le travail en est aux étapes d'évaluation et de planification de la procédure de réhabilitation des terres.

L'Inde reconnait depuis longtemps le besoin de réhabiliter les terres mais cela a été limité par des contraintes techniques, financières et sociales. Le développement industriel a eu des effets catastrophiques sur le couvert forestier du pays. La législation récente reconnait cette situation ainsi, par exemple, toutes les nouvelles mines doivent maintenant remplacer les terres forestières perturbées par l'activité minière par une surface équivalente nouvellement reboisée. Le remplacement ayant lieu durant la préparation du site minier et non à un certain moment durant la vie active de la mine.

La réhabilitation en Afrique du Sud a obtenu une reconnaissance mondiale grâce au développement d'une technique pour établir la végétation sur des haldes aurifères acides au moyen d'une irrigation par brumisateur. Il y a également d'autres techniques qui ont été développées pour revégéter ces dépôts. La réhabilitation d'autres dépôts métallifères et de déblais et stériles d'exploitations charbonnières est une pratique courante. En plus, il y a plusieurs programmes de recherche intensive en réhabilitation qui sont en cours.

Certains problèmes et réussites de réhabilitation de terres aux Indes, en Afrique du Sud et en Espagne seront décrits, avec l'influence des facteurs techniques, sociaux, politiques et économiques.

Projet intégré d'amélioration du sol et de l'eau en Egypte:
Programme d'amélioration du sol

S. El Gayar, L. A. Leskiw et K. Pohjakas

L'Agence Canadienne de Développement International en coopération avec le Gouvernement égyptien conduit un projet d'amélioration des terres de plusieurs millions de dollars. Ce projet, d'une durée de 5 ans, porte sur 30000 ha dans le delta du Nil.

Les sols de la majeure partie de la surface du projet, et d'une bonne part du delta du Nil, ont un niveau d'eau élevé et de graves problèmes de salinité et de sodicité, d'où le besoin de réhabiliter les terres à grande échelle. Afin d'améliorer les sols, ce projet utilise une approche intégrée constituée de plusieurs éléments clé: assemblage de données de base, améliorations du système d'irrigation, du drainage et du sol, services, développement social, formation et gestion de projet. Cette présentation se concentre sur l'amélioration du sol laquelle implique le travail du sous-sol, des applications de gypse, le nivellement des terres, aussi bien que les relations avec les autres éléments. Les conditions des sols et agro-écologiques sont soulignées: les activités planifiées de réhabilitation et les procédures d'évaluation sont présentées avec une emphase sur les aspects intégrés du projet.

Impact du climat sur le succès de la revégétation dans la région des contreforts et des montages d'Alberta, Canada

T. M. Macyk, Z. W. Widtman et V. Betts

Depuis 1972, le Conseil de Recherche d'Alberta a dirigé un programme de recherche en revégétation près de Grande Cache, en Alberta conjointement avec les opérations minières de surface de Smoky River Coal Limited. L'utilisation de techniques appropriées de manipulation du matériel et la sélection d'espèces végétales adéquates, combinées avec de bonnes pratiques gestionnaires, ont permis l'établissement de communautés végétales diverses qui autorisent différentes utilisations du territoire. Le climat a été reconnu comme étant le principal facteur limitant le succès de revégétation dans la région. Les enregistrements des précipitations se sont faits depuis le début du programme sur la base de la saison de croissance. Plus récemment, un équipement de contrôle continu a été installé pour mesurer les précipitations, la température de l'air et du sol, la direction et la vitesse du vent et l'humidité relative. La période sans gel s'est échelonnée de 45 à 107 jours durant les 4 dernières années. Dans certaines régions caractérisées par une couverture de graminées et de légumes, on a mesuré des températures du sol à 2 cm de profondeur de plus de 48 °C pendant plusieurs heures pour des journées consécutives. La mesure de la quantité de pluie et de l'intensité des évènements pluviaux suggère que la distribution de l'humidité est un peu moins efficace pour un bon établissement et une croissance des plantes. De grandes différences de plus de 100% dans les valeurs de précipitation arrivaient souvent entre des distances courtes de 0.5 km. Des relations entre la température de l'air, du sol et le vent ont été développées. Les données assemblées par le programme de contrôle sont utilisées pour affiner les procédures opérationnelles de revégétation utilisées dans la région.

NORTHERN and HIGH ALTITUDE RECLAMATION

Réhabilitation d'écosystèmes alpins sévèrement perturbés: Nouvelles perspectives

Ray W. Brown et Jeanne C. Chambers

Notre récente recherche sur la revégétation d'écosystèmes alpins sévèrement perturbés dans les montagnes de "Beartooth" au Montana porte sur l'utilisation de densités élevées d'ensemencement d'espèces graminées indigènes et par des taux élevés de fertilisation. Une couche superficielle de paillis de paille est habituellement utilisée et de la chaux hydratée incorporée dans les déchets de mine acide était utilisée lorsque nécessaire. Les résultats démontrent que ces méthodes tendent à exclure par compétition l'établissement d'autres espèces et de toutes formes de vie dans la communauté. Nous avons trouvé que de fortes applications d'azote en début de traitement n'ont pas augmenté les capacités de rétention des éléments nutritifs à long terme pour les sites perturbés, et que lorsque la fertilisation a été interrompue il y a eu un déclin rapide de la productivité du site, ce qui a davantage retardé l'établissement d'espèces. Lors des dernières années nous avons adopté de nouvelles perspectives en regard de la revégétation alpine qui se concentrent sur des approches plus fondamentales. Notre recherche suggère que les mélanges de graines pour les perturbations sévères devraient inclure, en plus des graminées, des espèces ayant des exigences nutritives faibles et la capacité de fixer l'azote, que les densités d'ensemencement soient réduites, et que des applications modérées de macro-nutriments devraient probablement résulter par une augmentation des taux de succession et par une richesse plus élevée en espèces. Les résultats montrent que les réponses des espèces aux méthodes de revégétation sont contrôlées par différentes caractéristiques physiologiques, par l'assemblage de graines spécifiques et les exigences d'entreposage, et que la viabilité des graines et la germination varient énormément d'une année à l'autre. Cette recherche suggère également que des additions de matière organique à décomposition lente rehaussent les capacités nutritives et de rétention d'eau du sol, qu'un paillis de surface augmente les capacités de retenir les graines et réduit la perte de particules fines du sol par érosion éolienne, et que la rétention des graines peut être améliorée par l'utilisation sélective de différentes rugosités de surface pour les sites perturbés.

L'utilisation d'espèces indigènes sélectionnées dans les programmes de revégétation subarctique

Lynn Maslen et G. Peter Kershaw

L'utilisation d'espèces indigènes dans les programmes de revégétation nordique est souvent recommandée mais rarement mise en application. Les raisons habituellement mentionnées incluent l'incapacité des espèces indigènes, par rapport aux espèces agronomiques, à s'établir rapidement, et le manque de disponibilité commerciale pour les graines. Une étude a été commencée afin d'évaluer le potentiel de revégétation d'espèces herbacées et arbustives indigènes aux environnements subarctiques, et de graines sélectionnées produites par des fermes expérimentales couramment en opération dans le Nord. Le site d'étude était une simulation de traçé de pipeline localisé dans la forêt subarctique dominée par Picea mariana, près de Fort Norman dans les Territoires du Nord-Ouest. Le substrat utilisé était dominé par le sol minéral exposé suite à une tranchée de pipeline simulée.

Les traitements de revégétation incluaient: des graines amassées localement (Arctagrostis latifolia, Carex membranacea, Ledum groenlandicum, Betula glandulosa, Vaccinium uliginosum, Arctostaphylos rubra, et Empetrum nigrum); des rhizomes amassés localement (Epilobium angustifolium); des graines cultivées obtenues de "The Plant Materials Center" en Alaska (Arctagrostis latifolia, Artemisia Tilesii, Calmagrostis canadensis), et de "Decora Landscaping" au Yukon (mélange de graines: Agropyron violaceum: 82%; Festuca ovina: 10%; Poa alpina: 5%; Poa glauca: 3%).

A la fin de la première saison de croissance, les traitements utilisant les graines cultivées ont produit une couverture plus élevée que pour les traitements utilisant les graines locales ($p<0.0001$), et l'Arctagrostis latifolia d'Alaska a produit un plus grand pourcentage de couverture que n'importe quel autre traitement. Le mélange d'Artemisia Tilesii et de Calmagrostis canadensis a produit la deuxième couverture la plus dense (16%), suivi par les rhizomes d'Epilobium angustifolium et le mélange de graines du Yukon (9% et 8% respectivement). Arctagrostis latifolia a été la meilleure espèce locale avec une couverture de 6%. Aucune des autres espèces locales n'a donné une couverture de plus de 1%. L'Arctagrostis latifolia d'Alaska a eu la production aérienne la plus élevée (68 g/m) parmi les autres traitements ($p<0.0001$). Il n'y a pas eu de différences de phytomasse entre tous les autres traitements ayant donné une couverture de plus de 1%. En dépit de la petite couverture produite par Ledum groenlandicum et Betula glandulosa (<1%) la germination et l'émergence lors de la première année étaient élevées pour les deux espèces, résultant en des densités moyennes d'ensemencement de 333 m-2 et 284 m-2 respectivement. Les autres espèces d'arbustes et Carex membranacea avaient des densités d'ensemencement < 3 m-2, à cause d'une pauvre germination.

Les résultats de la première saison de croissance suggèrent que, selon les caractéristiques du site, des espèces indigènes sélectionnées, particulièrement Arctagrostis latifolia, sont pertinentes pour être utilisées dans les programmes de revégétation subarctique et que la culture des espèces indigènes peut améliorer leur pertinence pour l'usage.

La revégétation dans le nord canadien: un survol de 15 ans

W. Younkin et H. Martens

Le développement des ressources dans le nord canadien existe depuis des décennies, cependant, depuis les 15 dernières années sa vitesse s'est augmentée, sous l'influence de la recherche du pétrole et du gaz. Avec cette activité est venu un large éventail de perturbation du terrain et de la surface nécessitant une réhabilitation, c'est-à-dire la stabilisation et la revégétation. L'environnement nordique pose certains problèmes pour la revégétation à cause de la saison de croissance trop courte et le contenu élevé de glace dans le sol. Les terres au nord du 60ième parallèle présentent également une vaste étendue de conditions de site, de sol et de climat. A cause de la dureté de l'environnement nordique et du manque de matériel végétal adapté, l'emphase majeure de la recherche en réhabilitation a été mise en revégétation sur l'établissement d'un couvert végétal protecteur.

Les études de revégétation dans le nord canadien ont commencé au début des années 1970. Depuis, plusieurs études et essais ont été menés sur une large surface géographique. Ces essais portent sur les espèces, les mélanges d'ensemencement, les fertilisants, les paillis et les travaux du sol. Ces études sont revues et les découvertes à long terme résumées, en incluant des discussions sur les taux de développement du couvert végétal, sur la longévité, l'invasion d'espèces et le contrôle de l'érosion en concluant avec des spécifications pour la revégétation du nord canadien.

Défis de réhabilitation à la mine de charbon Usibelli à Healy, Alaska

Larry P. Jackson

La réhabilitation dans un environnement subarctique demande une compréhension profonde de la manière dont les températures en-dessous de zéro peuvent affecter le sol, l'eau et la végétation.

La mine de charbon d'Usibelli est située dans une région qui contient des zones de permafrost. La présence du permafrost nécessite une attention particulière car lorsque le sol est perturbé il dégèlera éventuellement. Le type de matériel dans lequel se trouve le permafrost détermine les options que nous avons dans la stabilisation et le maintien de la végétation sur le matériel.

Alors qu'une analyse des conditions du sol est menée, une étude plus détaillée est faite pour déterminer quel type de mesures de contrôle de l'eau doit être considéré étant donné la présence d'un sol contenant beaucoup de glace. Les mesures de contrôle de l'eau qui seront utilisées ne sont habituellement pas essayées sur le terrain. Cela conduit autant à des résultats agréables que désagréables.

Le projet de contrôle de l'eau contient aussi un contrôle de l'érosion. Le contrôle de l'érosion est l'un des défis les plus importants dans la réhabilitation de la région de Healy. Le type de drainage représente l'une des régions parmi les plus susceptibles au monde à l'érosion naturelle. Cela présente des défis afin de réduire l'érosion des sites restaurés et de rencontrer les standards de qualité pour l'eau.

Un des éléments importants pour s'assurer du succès d'un programme de réhabilitation est de n'avoir aucune idée préconçue sur ce qui va arriver par la suite. Chaque projet qui est prévu et exécuté est généralement un nouvel essai dans un environnement particulier. A cause du manque de projets semblables cela fait que chaque jour est une aventure.

Eléments affectant la germination de graines herbacées alpines en relation avec leur utilisation potentielle pour la revégétation.

Surya N. Acharya

Des études de germination avec Poa alpina L. et Agropyron latiglume L. ont été entreprises pour déterminer les conditions optimums de germination, la présence de période de dormance chez les graines et l'étendue de la variabilité parmi les populations pour la vitesse de germination. Les graines de Poa alpina ont eu une meilleure germination en obscurité et des cycles de températures de 22/15 °C pour 16 /8 hrs., alors que A. latiglume avait besoin d'un régime de 29/22 °C et d'obscurité pour une meilleure germination. Une germination rapide des deux espèces a eu lieu à l'intérieur d'une marge étroite de conditions de température. Des conditions de lumière et de température sous l'optimum ont semblé avoir un effet inhibiteur sur la germination des graines durant la période initiale d'imbibition. L'inhibition de la germination par des facteurs externes (dormance secondaire) et la présence d'une dormance primaire pour les graines de la pépinière peuvent être leur adaptation à des environnements alpins extrêmement difficiles. Cela et la présence de différences parmi les populations pour la germination des graines pour les deux espèces sont encourageants pour notre programme de reproduction qui tente de sélectionner les génotypes avec une capacité de germination améliorée tout en maintenant une adaptation aux environnements difficiles.

Comportement de floraison de populations de Poa alpina sous conditions contrôlées

R. Hermesh et S. N. Acharya

Pour déterminer l'existence de populations de Poa alpina L. localement adaptées dans les Montagnes Rocheuses d'Alberta, des touffes d'herbes ont été amassées à partir d'environnements alpin et subalpin pour deux latitudes. Des clones de sept touffes, représentant chaque population, ont été testés simultanément dans des chambres de croissance utilisant des régimes de température froide (8/1 °C), moyenne (15/8 °C) et chaude (22/15 °C) avec une photopériode de 16 hrs. Huit caractéristiques de reproduction ont été mesurées pour chaque clone. Après une période de 6 mois, les clones du régime de température froide ont produit des panicules normales. Cependant, la floraison et la maturité des graines étaient considérablement retardées comparativement aux deux autres regimes. Les clones de l'environnement alpin élevé (2700 m) ont eu plus de fleurs et de graines que les clones de l'environnement subalpin. Au régime de température moyenne, les panicules initiales étaient normales, par la suite plusieurs plants ont produit des panicules anormales et vivipares. La production de bulbilles vivipares peut cependant être renversé en changeant les conditions de croissance. Les clones du régime de température élevée ont produit très peu de panicules et la plupart étaient anormales ou vivipares. En général, les populations alpines et subalpines s'étaient adaptées à des conditions de température froide, cependant l'adaptation spécifique variait parmi les populations. La pertinence de ces observations pour la revégétation sera discutée.

Pourquoi les prairies alpines sont-elles vertes?

S. N. Acharya, R. N. Coleman, M. Neuwirth et M. Dalpe

Des échantillons de sol pris dans la rhizosphère de Poa alpina et Trisetum spicatum à la montagne "Lookout" contenaient des nombres plus élevés de bactéries que le sol éloigné de 3 cm. Les échantillons de rhizosphère pris pour 9 plants différents (pour les deux espèces) et mesurés pendant deux ans, contenaient au moins 10 fois plus de bactéries que les échantillons hors de la rhizosphère. Le nombre de bactéries calculé sur les médium d'azote libre variait de 5 à 56% des espèces hétérotrophiques. Les organismes qui croissaient facilement sur les médiums d'azote libre après 6 transferts successifs ont été identifiés comme étant Xanthobacter flavus, X. autotrophicus, Azotobacter beijerincki, Azomonas macrocytogenes, Flavobacterium multivorum, F. aquatile et Beijjerinckia indica. L'identification de l'espèce de certains Xanthobacter n'était pas possible car ce genre n'a pas été complètement décrit. Plus de bactéries fixatrices d'azote ont été isolées de la rhizosphère de P. alpina comparativement à celle de T. spicatum en dépit de leur proximité (<1m). Les semis de P. alpina inoculés avec des bactéries fixatrices d'azote sont restés verts et en santé pour une période beaucoup plus longue que pour les semis non inoculés croissants dans un médium d'azote libre. La microscopie électronique des racines des semis inoculés et des bulbes plantés dans le sol de la Montagne "Lookout" a révélé leur étroite relation avec la bactérie. La signification d'une relation symbiotique libre en relation avec la revégétation de perturbations alpines sera discutée.

Réhabilitation expérimentale dans les Appalaches: Pratique expérimentale à Amos Ridge, 1984-1988

Carl E. Zipper, W. Lee Daniels et James C. Bell

La compagnie Amos Ridge Coal a fait de l'extraction minière sur des pentes abruptes dans le comté de Wise en Virginie depuis la moitié des années 60. Sur une période s'étendant du 1er janvier 1984 jusqu'en septembre 1988, la compagnie opérait sous un permis permettant une pratique expérimentale différant des règlements de l'industrie minière de surface pour le charbon en Virginie, comme prescrit par la section 711 de la Loi du contrôle de l'industrie minière de surface et de la réhabilitation (Surface Mining Control and Reclamation Act, SMCRA).

Tous les standards de performance environnementale de la SMCRA ont été respectés pendant les opérations minières, à l'exception de ceux mis de côté lors de l'expérimentation. Ceux-ci avaient rapport aux standards de construction en matière de remplissage, et le régalage à une topographie proche de l'originale. Trois sites de remplissage de déblais ont été construits, un en utilisant les pratiques standards et deux en prenant les techniques expérimentales.

Approximativement 10 acres de terrain plat avec des sols profonds ont été produits à partir de la perturbation de 70 acres.

Les données amassées sur le site pour la période de 1984-1988 nous donnent les résultats de la pratique expérimentale. Les données des coûts d'opération indiquent des différences de coûts parmi les méthodes de remplissage, avec une meilleure efficacité économique pour la méthode dite du "rock-core chimney drain" par rapport aux techniques de remplissage dites "durable rock fill" et "underdrain fill". Des piézomètres pneumatiques installés dans les remplissages ne montraient pas de différences en termes d'augmentation d'eau de porosité: tous se drainant librement. Egalement, les données sur la qualité de l'eau indiquent aucune conséquence défavorable pour la qualité de l'eau souterraine ou de surface. Une analyse des coûts d'exploitation minière sur la période de 1985 combinée avec des techniques de modélisation informatique, indique que le coût de l'exploitation minière sous les pratiques expérimentales était moindre que le coût probable, que les pratiques de restauration pour les contours avaient été employées, alors que la récupération du charbon était plus grande. Une analyse comparative du potentiel à l'érosion pour la surface réhabilitée et pour une surface produite par la restauration conventionnelle, a montré que la forme expérimentale était beaucoup moins érosive.

Les résultats de la pratique expérimentale indiquent que, lors qu'adéquatement exécutée sur le terrain approprié, la méthode de restauration expérimentale employée à Amos Ridge peut réduire les impacts environnementaux et les coûts de l'exploitation minière sur les terrains en pentes abruptes tout en augmentant la récupération du charbon et les potentiels d'utilisation du territoire.

FISH & WILDLIFE and RANGELAND RECLAMATION

Utilisation de l'habitat et alimentation de l'orignal et du chevreuil sur une mine réhabilitée dans le centre-ouest de l'Alberta

N. A. Roe et A. J. Kennedy

L'utilisation, par l'orignal et le chevreuil, d'une mine de charbon restaurée et de l'habitat naturel adjacent a été surveillée entre 1978 et 1985 au centre-ouest de l'Alberta. Les objectifs étaient de déterminer l'utilisation de l'habitat, d'évaluer l'utilisation d'arbustes décidus plantés et de documenter les régimes alimentaires de l'orignal et du chevreuil. Le site étudié a été semé au départ avec des graminées, de la luzerne et du trèfle. En 1979, des semis de pin lodgepole et d'épinette blanche ont été plantés à 1250 tiges/ha; de plus 3 îlots de saule ont été plantés. Les habitats adjacents étaient constitués de forêts de conifères et mixtes dominées par le pin lodgepole, l'épinette noire, l'épinette blanche, le peuplier faux-tremble et le peuplier baumier. L'orignal et le chevreuil ont fait une utilisation comparable ou plus grande de la surface restaurée par rapport aux types d'habitat non perturbés. L'utilisation de la surface restaurée a été très variable d'une année à l'autre, sans tendance claire pour une augmentation ou une diminution dans l'utilisation, autant pour l'orignal que pour le chevreuil. La variation dans l'utilisation des habitats adjacents non perturbés a été moins prononcée. Les niveaux moyens d'utilisation du site de la mine étaient plus élevés que pour l'habitat adjacent, mais pas de façon significative pour l'orignal ($p>0.05$), et à peine significatif pour le chevreuil ($0.05<p<0.10$). Le chevreuil a fait une utilisation double du site de la mine comparativement à l'orignal, mais la différence n'était pas significative sur une base année après année. L'analyse des fèces a révélé que le régime alimentaire de l'orignal était composé principalement de saule (88%) et d'épinette (8%). La diète du chevreuil était composée principalement de cornus (31%), légumes (23%), equisetum (15%) et de peuplier (6%).

Les arbustes de saules ont été régulièrement broutés entre 1981 et 1985 (74% de la plantation), alors que le broutage était catégorisé de lourd (26 % des plantations évalués) ou de modéré (20%). Les résultats indiquent que l'orignal et le chevreuil vont facilement prendre le fourrage dans les surfaces restaurées si des arbustes décidus, des buissons et des légumes sont plantés, mais que les graminées semées pour la stabilisation initiale du sol seront modérément utilisées.

Changements dans l'habitat et les populations de poissons au croisement d'un pipeline réhabilité et de la rivière Raven, Alberta

J. H. Allen et A. Lees

Entre 1964 et 1973, deux pipelines de large diamètre et une ligne de transmission d'énergie ont été construits avec plusieurs droits de passage à travers la rivière Raven dans l'ouest de l'Alberta. Le lit de la rivière à l'intérieur du droit de passage était large et peu profond, avait peu d'abri pour les poissons; les abords manquaient également d'une communauté végétale riveraine stable. Très peu de restauration naturelle de l'habitat des poissons a eu lieu à l'intérieur du lit dérangé depuis la dernière perturbation. En 1984, un projet a été initié afin de réhabiliter le lit et d'évaluer les effets de la restauration sur l'habitat et les populations de poissons. Trois constituants de l'abri; surplomb des rives, rondins, souches et débris et la végétation aquatique, ont été mesurés 5 fois entre août 1984 et août 1987 et les populations de poissons examinées à l'aide de moyens électroniques pour avoir des données sur l'abondance, l'âge, la croissance et l'utilisation de l'habitat. Les mesures de restauration ont augmenté la quantité d'habitats disponibles et les populations de jeunes truites de l'année dans la section restaurée ont augmentée significativement en dépit de l'impact majeur d'une inondation en juillet 1986. Les résultats de l'étude suggèrent également que l'effectif chez la truite brune était dépendant du volume de la décharge du cours d'eau durant la période de frai. A cause de la variabilité des facteurs environnementaux et de leurs effects, cela prendra probablement quelques années avant que les populations de poissons atteignent un état d'équilibre avec le nouvel habitat créé dans la section restaurée.

Distribution saisonnière et spatiale des mouflons à Cardinal River Coals Ltd.

Beth MacCallum

L'activité minière de Cardinal River Coals Ltd. a radicalement changé le paysage en partant d'une forêt dense de conifères pour devenir un terrain ouvert constitué de prairies restaurées à proximité d'amoncellements non restaurés. Une population d'environ 200 mouflons utilise couramment la région une bonne partie de l'année. Des études conduites depuis l'automne 1985 jusqu'à l'hiver 1987 ont identifié des patrons d'utilisation saisonnère et spatiale pour les superficies actives, partiellement et complètement restaurées. Les habitats pour le prérut, le rut, les saisons d'hiver et de printemps se retrouvent à différents endroits dans la région, aussi bien que pour les endroits de mise bas et les sites de léchage du minerai. Les hauts murs des excavations épuisées sont utilisés comme terrain de fuite et routes de voyage. Les recommandations au Conseil de conservation et de réhabilitation des terres d'Alberta, pour le maintien des hauts murs et des prairies restaurées comme étant des composantes intégrales de l'habitat du mouflon, ont été acceptées et réalisées dans la réhabilitation finale du paysage.

La création d'un lac de pêche sportive à Cardinal River Coals Ltd.

G. B. Acott

La Cardinal River Coals Ltd. produit annuellement 2 millions de tonnes de charbon cokéfié pour le marché d'exportation. La compagnie opère depuis 1969 et a fait des progrès substantiels dans ses programmes environnementaux et de réhabilitation. L'idée principale en réhabilitation pour la CRC Ltd. est le développement d'un habitat faunique sauvage avec une emphase particulière sur les mouflons. Un deuxième objectif pour le développement récréatif a été la création d'un lac. La formation du contour des berges, la construction de la zone du littoral, l'inoculation de macrophytes et des techniques de mise en valeur de l'habitat en aval ont été utilisés pour tenter d'avoir une pêche sportive viable. Jusqu'à maintenant le progrès a été surveillé par une étude limnologique continue pour déterminer le taux de développemnt de la chaîne alimentaire conduisant à des recommandations pour le programme d'ensemencement de poissons.

Utilisation de bassins de dragage pour former un habitat propice à la culture du saumon "chinook"

Carl Richards, Phillip J. Cernera et Michael P. Ramey

La rivère Yankee Fork en Idaho était historiquement un endroit pour la migration d'espèces saumonées, principalement pour le saumon de printemps "chinook" et la truite "steelhead". Ces migrations ont été réduites dramatiquement lors des 20-25 dernières années par la présence d'activités minières et les effets de développements hydroélectriques en aval. Les activités minières ont résulté dans le recreusage complet du lit de certaines portions de la rivière et le dépôt des résidus de dragage qui ont dégradé une grande partie de l'habitat de frai et de culture de la rivière Yankee Fork. Les études de pêche indiquaient que la production de saumon chinook dans cette rivière est limitée par la disponibilité d'habitat de culture, ce qui a eu comme résultat de diriger les efforts vers l'augmentation ou l'amélioration des espaces de culture disponibles. La rivière est bordée par plus de 30 bassins variables en dimension, forme et profondeur, ces derniers étant les vestiges des opérations de dragage. La plupart des bassins de draguage sont en dehors du lit de la rivière et n'ont pas de lien direct en surface. Des plans de génie ont été développés afin de raccorder les bassins de dragage à la rivère, de façon à augmenter les habitats de croissance utilisables. Quatre séries de bassins de draguage ont été construits, chacun contenant de 2 à 7 bassins raccordés en série. Les entrées et les sorties des bassins ont été faits pour faciliter l'accès aux jeunes saumons. L'ajout de ces bassins de draguage a augmenté la capacité de croissance de la rivière Yankee Fork de 24 000 individus.

Démonstration de pâturage sur des terres réhabilitées à la mine "Black Thunder" de la compagnie "Thunder Basin Coal", Comté de Campbell, Wyoming

Robert L. Moore Jr., Warren R. Keammerer et Edward J. DePuit

Un des standards dans le succès de revégétation est de démontrer que la communauté végétal ayant servie à la réhabilitation est capable de soutenir une pression de pâturage par les animaux domestiques et la faune sauvage qui soit au moins égale à la pression de pâturage avant l'exploitation minière. A ce jour, les superficies les plus agées et les plus vastes ayant été restaurées à la mine "Black Thunder" sont localisées à l'excavation nord. Les superficies qui ont été semées en 1981, 1982 et 1983 ont été utilisées pour préparer et construire un système de deux pâturages rotationnels qui portent sur 183 acres. Le projet à l'étude inclue la surveillance de la végétation pour connaitre l'utilisation des pâturages relativement au gain en poids de l'animal et pour déterminer des changements dans la végétation dûs au pâturage.

Des veaux (Black Angus-Hereford) seront utilisés en 1988, la première année de l'étude. Le projet à l'étude demande d'introduire le troupeau dans le pâturage ouest à la mi-mai après que les poids individuels se soient stabilisés. Le troupeau sera alors pesé et déplacé dans le pâturage est à la mi-juillet où il restera jusqu'à la mi-septembre, alors le troupeau sera pesé pour la troisième fois. Les données sur la végétation seront prises à la mi-juillet quand le troupeau est déplacé du premier pâturage au second et encore à la mi-septembre quand il sera enlevé du deuxième pâturage. Des données et de l'information résumant la première année de l'étude seront présentées.

Pâturage complémentaire de terres minières réhabilitées et d'habitats naturels au Montana

Edward J. DePuit et Joe G. Coenenberg

Une étude de trois ans a été faite pour évaluer la pertinence de la revégétation d'une mine de charbon avec des graminées et des légumes introduits comme site de pâturage complémentaire avec des pâtures naturelles. Les objectifs étaient de déterminer les réponses du sol et de la végétation à l'intérieur des pâtures de la mine suite au pâturage du troupeau, et d'évaluer la capacité des pâtures sur les mines pour supporter du bétail. Les traitements incluaient un site de contrôle sans pâturage; du pâturage rotationnel pour le printemps, l'été et l'automne pour le site minier exclusivement; du pâturage rotationel et complémentaire sur le site minier au printemps, sur les pâtures naturelles à l'été et de retour sur le site minier à l'automne. Les traitements ont été appliqués de façon identique chaque année pendant trois ans et l'intensité de pâturage a été modérée (50-65 % d'utilisation du fourrage). Les résultats indiquent que le pâturage de printemps et d'automne améliorent la productivité de la végétation sur le site minier, induisent certains changements dans la composition et la diversité des espèces végétales, et influencent positivement un bon nombre des attributs du sols. En conséquent, les pâtures sur le site minier ne font pas que résister mais bénéficient du régime de pâturage imposé. Les données sur la qualité du fourrage et sur le gain animal pour les pâtures sur le site minier démontrent la plus haute utilité du mélange d'espèces introduites pour le printemps, l'utilité la plus basse durant l'été (quand la performance animale sur les pâtures naturelles dépassait celle du site minier), et une utilité intermédiaire à l'automne. Les gains du troupeau pour la saison entière étaient plus élevés sous le système de pâturage complémentaire (habitat naturel et site minier) que sous le système de pâturage au site miner exclusivement, et étaient aussi généralement plus élevés que les gains atteints normalement pour un pâturage naturel dans la région. Ces résultats suggèrent qu'un pâturage complémentaire peut comprendre une utilisation productive de pâturages dominés par des espèces introduites quand de telles pâtures existent ou sont crées sur des sites miniers.

Mise sur pied d'un programme de mitigation des habitats fauniques pour le projet de barrage de la rivière Oldman

J.E. Green et A.L Nilson

Pour compesnser les pertes d'habitats fauniques associés au projet de barrage sur la rivière Oldman au sud de l'Alberta, un programme de mitigation a été mis sur pied afin d'instaurer des habitats alternatifs pour la faune dans la région immédiate du réservoir. Une stratégie spécifique a été élaborée en 1988 qui tient compte des exigences biologiques de la faune en matière de mouvements de migration et d'habitats spécialisés par exemples en relation avec l'utilisation du sol actuelle et future du réservoir et le potentiel pour l'établissement de boisés.

La mise en oeuvre de ce projet de mitigation est maintenant amorcée et implique trois techniques majeures soit la protection des habitats existants, l'amélioration des habitats perturbés et la création de nouveaux habitats. Environ 65 projets distincts sont développés en plus de quelques projets pour l'établissements de nids pour rapaces.

Différentes techniques de mitigation seront décrites avec de nombreux exemples dont (1) la protection des habitats, (2) la construction des barrages, (3) l'établissement de boisés utilisant un système d'irigation souterrain, (4) la création de zones marécageuses et (5) la modification des falaises pour les nids de rapaces et d'oies du Canada.

RECLAMATION and WATER

Réhabilitation de mines de manganèse abandonnées en le sud-ouest de Virginie et dans l'est du Tennessee

Jack A. Muncy

En 1985 la Tennessee Valley Authority (TVA) a initié le plan de réhabilitation du bassin de l'embranchement sud de la rivière Holston. L'objectif du plan est d'identifier et de chercher la résolution de tous les problèmes majeurs de la ressource eau dans la région du bassin par une gestion intégrée.

Une composante majeure du plan est liée aux efforts de la TVA d'amoindrir les impacts de pollution de l'eau par les mines abandonnées de manganèse par une réhabilitation sélective du territoire. Ces mines abandonnées ont opérées avant l'adoption des lois de l'Etat en matière de réhabilitation sur l'exploitation minière pour les minéraux autres que le charbon. La TVA a pris un rôle dominant en identifiant ce problème de qualité des terres et de l'eau parce qu'il n'y a aucun autre moyen disponible pour stabiliser ces terres qui ont des impacts néfastes sur l'eau. Par la coopération des efforts financiers avec le Service Forestier des Etats-Unis et 25 propriétaires terriens, 276 acres couvrant 59 sites miniers différents, dans le comté de Smyth en Virginie et les comtés de Johnson et Carter au Tennessee, ont été traités depuis 1985. Ce texte donne des informations sur les activités du projet impliquées dans la réhabilitation de ces terres sujettes à l'érosion. Le problème restant porte sur une superficie de près de 50 acres.

Régimes hydrologiques souterrains et réhabilitation du paysage des mines charbonnières de surface en Alberta

S.R. Moran, M.R. Trudell, T.M. Macyk

A l'aide d'une étude de huit ans sur l'hydrologie souterraine d'un paysage minier réhabilité nous avons reconnu deux régimes hydrologiques différents: sites des hautes terres et sites des basses terres.

Les sites de hautes terres, qui constituent la majeure partie des surfaces réhabilitées, sont généralement situés au-dessus du niveau du paysage d'avant l'opération minière et sont caractérisés par un terrain plat à ondulant. Plusieurs petites dépressions ovales d'environ 10 m par 20 m et aussi profondes que 0.5 m, qui ont été formées par la subsidence du sol, parsement le paysage. La présence d'eau de surface dans ces dépressions est éphémère et tend à être d'une superficie limitée, avec les bassins non reliés à la nappe phréatique. La recharge de l'eau souterraine arrive seulement sous les dépressions et est un évènement peu fréquent relié à la formation éphémère de bassins. Le retour des niveaux d'eau souterraine vers une configuration stable après l'activité minière est lent, demandant au moins plusieurs décennies. La nappe phréatique est à une profondeur considérable sous la surface du terrain, dans la plupart des cas, au moins de 5 m à 10 m sous la surface. Les sols tendent à être bien drainés. Le potentiel à la salinisation du sol est généralement bas et limité à la bordure autour des bassins d'eau éphémères dans les dépressions. Les sols reconstruits évoluent vers la formation de Chernozems sur la plus grande partie du terrain et vers des gleysols luvics dans les dépressions. Un développement limité de sols solonetzics peut arriver autour des dépressions où la roche-mère en-dessous du sous-sol est sodique.

Les sites des basses terres, qui constituent des surfaces restreintes dans les terres réhabilitées, sont généralement situées sous le niveau du paysage d'avant l'opération minière. Les sites des basses terres se développent partout où le sol de surface était mince, généralement moins que 4 à 5 fois l'épaisseur du charbon enlevé, et dans les environs des coupes finales. Les sites des basses terres occupent généralement plus le paysage réhabilité des surfaces minières anciennes que nouvelles. Des petites dépressions, comme celles dans les sites de hautes terres, se forment suite à la subsidence des résidus. En plus, les sites de basses terres sont caractérisés par de larges dépressions qui résultent des opérations minières. Parmi les origines de ces dépressions sont les coupes finales, les rampes d'accès et les routes de camionnage. La formation de bassins d'eau de surface arrive souvent dans les sites de basses terres où les bassins tendent à être permanents ou semi-permanents et sont reliés avec la nappe phréatique. Durant les premières étapes de saturation des résidus, la recharge de l'eau souterraine se fait plus ou moins continuellement par écoulement des bassins permanents. Le retour des niveaux d'eau souterraine vers une configuration stable après l'activité minière est rapide, demandant généralement pas plus de 5 à 10 ans. La nappe phréatique stable est près de la surface du sol sur une grande partie du site et généralement à une profondeur de 1 à 3 m. Une fois que l'équilibre d'après l'activité minière est atteint, les grands bassins sont des sites de décharge pour l'eau souterraine, au moins durant une partie de l'année. Les sols des sites de basses terres tendent à être pauvrement drainés et ont un potentiel élevé pour la salinisation du sol. Avec le temps, les sols reconstruits évoluent vers des Solonetzs et des Gleysols salins.

Réponses géomorphiques de pentes naturelles et restaurées suite à des évènements de précipitation au Wyoming

Terrence J. Toy

Des données sur le ruissellement et la sédimentation ont été amassées sur les sites de deux pentes naturelles et restaurées de la compagnie "Glenrock Coal". Le ruissellement par unité de surface pour un site nouvellement restauré excedait celui des sites naturels en dépit d'intensités moyennes de précipitation plus faibles; cependant, le ruissellement du site restauré plus ancien était actuellement moins que celui des sites naturels. La production de sédiments par unité de surface pour le site nouvellement restauré était plus élevé que les sites naturels alors que la production de sédiments pour l'ancien site restauré était dans la marge de celle des sites naturels. Les concentrations de sédiments des écoulements du site récemment restauré étaient très élevées, spécialement au début du relevé, et excédaient de beaucoup celles des sites naturels. Encore, les concentrations de sédiments du site anciennement restauré se trouvaient dans la marge des sites naturels. Il y avait des relations statistiques significatives entre le ruissellement par unité de surface et la production de sédiments par unité de surface, et entre le pourcentage de sable et d'argile dans les sédiments et les pourcentages pour les sols de surface. La comparaison de la sédimentation et des distributions des particules du sol suggère un entraînement et un transport sélectifs des éléments du sol. Finalement, l'évidence suggère que les surfaces restaurées peuvent approcher un semblant d'équilibre, analogue aux surfaces naturelles, dans environ cinq années.

Combinaison de techniques empiriques et géomorphiques de dimension pour la reconstruction de cours d'eau temporaires au nord-est duWyoming

Steve McIntosh

La reconstruction de cours d'eau temporaires doit être limitée à des méthodes pour le choix des dimensions où les prérequis n'excèdent pas ce que le constructeur peut faire en regard de ce qui se rapporte aux matériaux de construction. Le contrôle absolu du matériel demandé par l'élaboration de formules empiriques et la duplication précise de la topographie exigée par les modèles géomorphiques nécéssitent une demande de construction matérielle impossible à faire compte tenu des outils et techniques des opérations minières de surface modernes. Le sol, le remblai et la topographie créés par l'exploitation en découverte, et l'évolution imprévisible de chacun, rendent invalides les approches de design arithmétique et géomorphique utilisées comme seuls déterminants des caractéristiques du canal. Les canaux d'inondation majeure peuvent être dimensionnés en utilisant le modèle de Manning. Un canal pour une durée de 2 à 5 ans peut être établi au sol, selon la forme sinueuse du canal d'avant les opérations minières, dans le cours de la crue calculée mathématiquement. Des obstacles en coin stratégiquement placés imitent l'effet des obstacles du canal ellipsoïdal naturel et assurent les méandres pour les eaux retenues. Ce format de design démontre une faisabilité économique et logistique pour faire un canal qui est stable après les opérations minières et qui est l'équivalent en forme et en fonction d'un cours d'eau non perturbé.

SEDCAD - Modèle informatisé pour aider au design pour la sédimentation, l'érosion et l'écoulement

Richard C. Warner et Pamela Schwab

Le modèle SEDCAD a été développé pour aider les ingénieurs dans le design de systèmes de contrôle sur l'érosion, la sédimentation et la gestion des eaux pluviales. Le modèle a été fait selon le concept d'une station de travail en ingénierie de faible coût contenant un ordinateur personnel, un digitaliseur et une imprimante avec une matrice de points. Des utilités autonomes sont démontrées lesquelles donnent au modèle la capacité de dessiner rapidement des déviations, de dimensionner les caniveaux, de développer des valeurs d'écoulement de section pour les tubes d'égouttement et les déversoirs d'urgence; de déterminer les volumes de remblai; et d'incorporer le calcul de l'érosion pour les pentes abruptes selon l'équation USLE. Le modèle prédit et trace également les hydrographes et les sédimentographes pour les bassins de drainage et détermine l'efficacité des trappes de sédimentation.

Projet de réhabilitation et d'hydrologie sur les plaines (PHRP): Une étude interdisciplinaire dirigée vers l'optimisation de l'aptitude agricole après l'activité minière.

S.R. Moran, M.R. Trudell, T.M. Macyk, D. B. Cheel et Al Howard

Entre 1979 et 1987, le projet de réhabilitation et d'hydrologie sur les plaines a cherché nombre de solutions pour la réhabilitation des mines charbonnières de surface des plaines d'Alberta. Le but général du PHRP était: (1) de prédire le succès à long terme et les impacts hydrologiques des pratiques de réhabilitation courantes, et (2) de développer une technologie de restauration qui permettra la modification nécessaire de la pratique courante pour assurer le succès à long terme et mitiger les conséquences environnementales nuisibles. Le projet implique une approche globale de réhabilitation à travers l'intégration d'études sur la géologie, l'hydrologie et les sols, pas seulement sur la surface proposée pour l'exploitation minière mais aussi pour les régions adjacentes non exploitées.

L'équipe du projet a trouvé que l'aspect chimique de l'eau souterraine dans les déchets de mine est significativement dégradé relativement à celui existant dans les aquifères de charbon non perturbées. La salinité de l'eau souterraine après l'exploitation minière peut être expliquée entièrement en termes de contenu en sels de la gangue avant les opérations minières. Même si une altération limitée des résidus arrive, il n'y a pas d'évidence que l'oxidation des sulfides contribue significativement aux caractéristiques chimiques de l'eau souterraine dans les déchets pour les plaines d'Alberta. Sur la base de ces découvertes, l'équipe du projet PHRP concluait que la manipulation sélective ou le placement des résidus ou des matériaux du sous-sol ne feraient pas diminuer la salinité de l'eau souterraine des résidus.

L'équipe du projet PHRP concluait que l'exploitation charbonnière en surface dans les plaines d'Alberta ne devrait pas avoir d'effets nuisibles sur la qualité de l'eau souterraine ou de surface en dehors des superficies minières. L'évidence suggère que l'eau souterraine provenant des résidus ne se déchargera pas dans les courants de surface à un taux suffisament rapide pour altérer sensiblement la chimie de l'eau. L'évidence de la migration de l'eau souterraine provenant des résidus vers les aquifères non minières a été observée dans un cas isolé avec une combinaison relativement rare de la stratigraphie de la gangue et de la configuration topographique des résidus. L'activité minière a toutefois des effets nuisibles sur les ressources en eau souterraine à l'intérieur des petites superficies qui sont exploitées. Dans les régions sous lesquelles on trouve du charbon exploitable en surface, les provisions d'eau pour l'agriculture sont habituellement obtenues de puits faits dans des lits fracturés dans le charbon ou dans des lits sableux au-dessus du charbon. L'exploitation de surface enlève ces aquifères peu profondes. Dans certaines régions, le remplacement des provisions d'eau sera disponible à partir de lits sableux et rocheux sous la zone de charbon"Lower Horseshoe Canyon".

L'implication environnementale la plus significative pour l'eau souterraine des résidus est pour la salinisation du sol des paysages reconstruits. Une telle salinisation peut se développer où la nappe phréatique est maintenue à l'intérieur d'une profondeur d'environ 1.5 m de la surface du sol par des mouvements latéraux ou ascensionnels de l'eau durant la période de croissance. Ces conditions d'une nappe phréatique peu profonde se développent relativement rapidement, à l'intérieur de 10 à 15 ans, dans les basses terres des superficies restaurées. Dans ces régions, des dépressions en bassins facilitent la recharge de l'eau souterraine, qui conduit à un développement rapide des conditions d'une nappe phréatique peu profonde dans les régions adjacentes aux dépressions. Où les hautes terres des superficies restaurées sont plates ou avec une pente très faible, les nombreuses petites dépressions qui se forment en réponse aux dépositions variables des résidus permettent la création de bassins éphémères et la recharge de l'eau souterraine. Où le flux de la recharge est suffisament grand, l'eau souterraine s'écoule vers les régions plus basses en augmentant davantage la salinisation à ces endroits. L'équipe du projet PHRP concluaient que la mise en forme des terres restaurées pour former des pentes avec un drainage intégré minimiserait le potentiel de salinisation du sol en diminuant la recharge en eau souterraine.

L'aptitude agricole des sols reconstruits, qui a été évaluée en utilisant un système développé par le projet PHRP, a été trouvée équivalente à l'aptitude d'avant les opérations minières. La différence principale était que les taux d'aptitude des sols reconstruits étaient plus homogènes que pour les terres non exploitées. Les taux les plus élevés et les plus bas d'avant l'activité minière semblent s'être perdus dans le mélange des matériaux de la gangue qui est survenu durant les activités minières et la réhabilitation. L'évidence suggère que les propriétés physiques et chimiques des sols reconstruits bien drainés s'améliorent avec le temps avec une diminution du contenu en sodium démontrant l'écoulement vers le bas et une diminution de la densité volumétrique. Une autre évidence suggère qu'une dégradation de l'aptitude arrive suite à une augmentation de l'humidité en surface. Les dépressions formées par la subsidence, qui habituellement ne sont pas complètement développées avant plusieurs années après la mise en forme finale, résultent en la création de bassins éphémères.

HERBACEOUS REVEGETATION

Fourrage natif prometteur pour l'ensemencement/ mélange de graines pour déchets de mines

Ardell J. Bjugstad

Trente espèces pérennes de fourrage ont été semées directement sur des déchets de mine de charbon sur une période de deux ans. Celles qui démontraient une excellente émergence des graines et une croissance vigoureuse pour les deux années étaient: Petalostemum candidum, Glycyrrhiza lepidota, Ratibida columnifera, Liatris punctata et Astragalus ceramicus. Les espèces semées les deux années mais ayant une germination acceptable pour seulement une année étaient: Aster ptarmicoides, Echinacea angustifolia, Solidago missouriensis, Astragalus striatus, Petalstemum purpureum et Metzelia decapetala. Les autres espèces ont montré très peu ou aucune germination d'où la difficulté d'établir ces espèces directement par l'ensemencement sur les déchets de mine de charbon.

Diversité et variété saisonnière des espèces indigènes dans les prairies restaurées

K. J. Hirsch et D.J. Nilson

Dans un endroit semé de graminées indigènes, les espèces graminées de saison froide prédominent souvent sur les espèces de saison chaude. Des mesures sur le terrain ont été prises pour évaluer l'effet de traitements utilisés pour redonner la balance saisonnière à un endroit semé de graminées indigènes dominées par les espèces de saison froide. Une prairie restaurée par des espèces indigènes, lourdement dominée par Agropyron intermedium et Agropyron trichophorum, contenait seulement une infime quantité de graminées de saison chaude. Du glyphosate (Roundup) a été pulvérisé par avion en directions perpendiculaires créant un patron d'échiquier avec des taux d'application de 0, 1.75 et 3.50 l/ha. Ces techniques d'application d'herbicide n'étaient pas sans avoir certaines dérivations. Après que l'herbicide ait fait effet, la surface a été brûlée et semée avec un mélange de graminées de saison chaude. Une partie de la surface originellement semée a été retenue comme contrôle. Les traitements appliqués ont eu des effets significatifs sur la balance saisonnière. La proportion de graminées de saison chaude a augmenté sur les surfaces qui ont reçu les plus hauts taux de glyphosate. Les espèces de saison chaude, incluant Bouteloua gracilis, Bouteloua curtipendula et Andropogon scoparius ont remplacé Agropyron intermedium et Agropyron trichophorum. Les surfaces traitées avec 3.50 l/ha de glyphosate avaient plus de 50 % d'espèces de saison chaude. La production totale cependant était réduite pour les taux les plus élevés d'herbicides. Le taux de 0 l/ha de glyphosate combiné avec les traitements de brûlage et d'ensemencement a donné la production la plus élevée. En résumé, l'utilisation de glyphosate suivie de brûlage et d'ensemencement peut accroître réellement la diversité et la variété saisonnière d'un endroit où l'ensemencement est établi.

Productivité de plants agronomiques et indigènes sous des taux variés d'application de graines et de fertilisants sur un corridor de transport simulé, à Fort Norman, Territoires du Nord-Ouest

Kevin Evans et G. Peter Kershaw

Au printemps de 1987 une étude de revégétation a été initiée sur un droit de passage orienté est-ouest sur le site d'étude de la SEEDS avec l'idée de savoir de quelles façons des taux variés de fertilisants et d'application de graines affecteraient la revégétation d'un corridor de transport simulé. La portion du droit de passage pour cette étude a été perturbée par 1800 passages d'un ATC (Honda 200M) de façon à simuler plus exactement un corridor de transport nordique. La surface à l'étude a été semée et fertilisée selon des taux similaires à ceux employés dans les projets de revégétation du Nord. Le mélange de graines était identique à celui utilisé par "Interprovincial Pipe Line Ltd" pour leur pipeline de Norman Wells à Zama Lake. Ce mélange contenait les espèces agronomiques suivantes - Poa pratensis: 5 %; Festuca rubra: 20%; Festuca ovina;15%; Agropyron trachycaulum: 28%; Alopecurus arundinaceus: 15%; Phalaris arundinacea: 12% et Phleum pratense: 5% semées au taux de 30 kg/ha. Un fertilisant complet (17-25-15) a été appliqué selon six taux (0, 100, 250, 400, 500 et 1000 kg/ha) avec et sans le mélange de graines.

A la fin des saisons de croissance de 1987 et 1988 des estimations de couverture ont été faites sur chacun des douze traitements de graines et fertilisation. Pour achever l'estimation des couvertures, la densité des espèces végétales a été mesurée en plus d'un échantillonnage de la biomasse pour chacun des traitements. La densité des plants dans l'échantillon de contrôle était de 198.4 individus/m^2 en 1987 augmentant à 460.8 individus/m^2 en 1988. L'accroissement en pourcentage pour la densité n'a pas été aussi élevée pour les autres traitements sans graines exception faite pour celui dont la fertilisation était de 400 kh/ha avec comme résultat que le nombre de plants est passé de 178.2/m^2 à 611.2/m^2. Cela a été une augmentation de densité de 253% pour une saison de croissance. Comme attendu, les traitements qui ont été semés avaient des valeurs de densité plus élevées. Dans le traitement semé et non fertilisé la densité des plants est passée de 401.6/m^2 en 1987 à 489.6/m^2 en 1988. Le traitement dans lequel 400 kg/ha de fertilisant et 30 kg /ha de graines ont été mis avait 520 plants/m^2 en 1987 et 721.4 plants /m^2 en 1988.

Le pourcentage d'accroissement pour les valeurs de densité était similaire pour chacun des six taux d'application de fertilisant, autant avec graines que sans graines. Cependant, le nombre d'individus par échantillon augmentait comme résultat de l'application de graines. Des tendances similaires pour la biomasse et la couverture ont été observées pour les traitements.

Utilisation d'une association Rhizobium-trèfle pour la revégétation de déchets d'une mine de lignite

Pamela A. Harris et David A. Zuberer

Les places-échantillons sur le terrain ont été établies sur des déchets de mine de lignite fraîchement nivelés à l'automne de 1986 pour étudier les effets de la fertilisation et de l'inoculation avec *Rhizobium leguminosarum trifolii* sur l'établissement et la croissance de *Trifolium subterraneum* et d'évaluer la survie de Rhizobium sur les déchets de mine. En 1987, les rendements en trèfle étaient plus élevés pour les places inoculées quand P et K étaient ajoutés. Les rendements n'étaient pas augmentés par l'addition de N. Des rendements plus faibles ont été trouvés dans les places non fertilisées avec ou sans inoculation. En 1988, des rendements en trèfle plus grands ont été observés pour les places fertilisées avec ou sans inoculation. Les rendements totaux moyens en 1988 étaient approximativement le double de ceux obtenus en 1987, cela provenait du couvert de plants plus dense obtenu par l'ensemencement naturel du trèfle.

Après l'émergence initiale du trèfle en 1986, les populations indigènes de Rhizobium trouvées dans les places non inoculées étaient plus grandes comparativement aux places inoculées. Les rhizobiums indigènes étaient en association efficace avec le trèfle, mais la production de matière sèche était plus basse pour les places non inoculées durant la première année. Autant les places inoculées que non inoculées avaient des populations de 104 à 105 rhizobium /g sol à la sénescence du trèfle. Les places de contrôle n'ayant pas de trèfle avaient approximativement 102 rhizobium/g sol. Les populations de Rhizobium dans les places inoculées et non inoculées avaient approximativement 103 rhizobium/g sol à l'émergence du trèfle lors de la seconde année, et ces populations étaient efficaces pour noduler le trèfle émergant.

L'utilisation du sorgho comme culture d'étude pour la restauration de terres agricoles de premier choix

R.I. Barnhisel et J.L. Powell

Des données seront présentées pour résumer trois expériences ayant les objectifs suivants: 1) Déterminer le potentiel de production de variétés sélectionnées de sorgho. 2) Déterminer l'effet de la profondeur du sol et l'histoire des récoltes antérieures sur la production du sorgho. 3) Déterminer l'effet, sur la production du sorgho, de fertiliser avec de la chaux le sous-sol avant le remplacement du sol de surface.

En général, le sorgho donne une bonne culture d'étude pour l'évaluation du succès de la restauration (i.e. la productivité) des terres agricoles de premier choix, cependant, de grandes variations se présentent entre les variétés. Le sorgho répondait à une augmentation de la profondeur du sol avec la plus grande production pour les traitements entre 20 et 60 cm de profond et une moindre productivité pour les traitements entre 60 et 100 cm. L'histoire des récoltes antérieures a affecté les productions de sorgho pour les places ayant été cultivées avec de la luzerne et de la fétuque durant les 5 premières années de l'étude, surpassant les places qui avaient une rotation de maïs-blé-soya. L'application de chaux au sous-sol acide a résulté dans une réponse significative pour la productivité.

WOODY PLANT REVEGETATION and SUCCESSION

Détermination des densités optimales de plantation pour la revégétation minière

P. Guy

A ce jour, il n'y a pas d'exigences dans la législation albertaine qui traitent de façon spécifique de la création d'habitat pour la faune sauvage durant la réhabilitation. Parce que les densités et la composition des espèces végétales des habitats fauniques à atteindre pour les surfaces réhabilitées doivent être adaptées à la zone écologique de la région, elles sont faciles à déterminer par comparaison. La détermination des densités végétales et des espèces à être plantées au début de la réhabilitation d'un site vers un habitat faunique est un problème plus complexe. Ce texte décrira les avantages et les désavantages de densités de plantation élevées et basses lors de la revégétation d'une surface minière, et décrit des façons de déterminer les densités de plantation appropriées en utilisant les caractéristiques sylviculturales des espèces arbustives et arborescentes utilisées en revégétation.

Revégétation et surveillance écologique d'une mine de phosphate

P. Soni et N.B. Vasistha

Le développement de pratiques de revégétation écologiques et économiques pour stabiliser les terres d'une mine à ciel ouvert est un défi. Surtout lorsque le site a des pentes abruptes associées avec des problèmes de glissements de terrain, d'érosion et de pollution des cours d'eau.

Ce texte présente les résultats d'un programme de revégétation pour stabiliser une surface minière où du phosphate a été extrait. Le programme met l'emphase sur l'utilisation d'espèces végétales écologiquement, économiquement et socialement intéressantes pour avoir une revégétation du site minier dégradé dans un laps de temps de six années.

De plus, des données ont été présentées sur la diversité de genres et d'espèces et sur la succession de la flore et de la faune en relation aux changements physiques et chimiques du sol suite à la revégétation.

Réhabilitation successionnelle dans l'ouest canadien: nouvelles idées sur un vieux sujet

David F. Polster

La réhabilitation successionnelle est définie comme la mise en valeur des processus naturels de succession pour la réhabilitation de sites fortement perturbés. La formulation de mélanges de graines de légumes et de graminées qui améliorent les processus naturels de succession est décrite. L'utilisation d'espèces ligneuses pionnières majeures et les dynamiques de succession végétale sont discutées dans un contexte de réhabilitation de sites dans l'ouest canadien. Les bénéfices de l'utilisation d'une approche basée sur la succession en termes de performance d'espèces améliorées, de diminution des coûts, et d'amélioration de la stabilité écologique sont discutés. Le développement de techniques de bioingénierie à utiliser sur des sites difficiles est discuté avec des références sur les techniques, les coûts et les bénéfices. Des facteurs clés lors de la planification d'un programme de réhabilitation successionnelle sont détaillés. Des exemples sont démontrés pour des programmes de réhabilitation conduits sur des sites miniers et industriels.

Première année d'évaluation de tampons protecteurs sur Pinus taeda L.

Walter H. Davidson

Au printemps de 1988 nous avons fait une petite étude pour évaluer les effects de tampons protecteurs sur la survie et la croissance du pin loblolly. Deux types de tampons ont été utilisés: Les tampons TREGRO type 100 et type 200 de la compagnie American Excelsior. Des semis de pin loblolly à racines nues 1-0 ont été plantés à la pioche le 14 avril et les tampons protecteurs installés le 15 avril. Le design de l'étude était distribué au hazard avec des semis avec traitement (tampon) et des semis-contrôle (sans tampon). Une évaluation faite le 5 mai a montré une survie inconstante attribuée à la technique de plantation. Il y avait trois personnes qui plantaient les semis. Deux ont eu des taux de survie de 95% alors que le taux de survie pour le troisième planteur était de 77%. L'évaluation à la fin de la saison de croissance montrait que les tampons n'avaient pas eu d'influence apparente sur la survie. La survie était de 72% pour les tampons et de 71% sans tampons. Heureusement, la mortalité initiale était plutôt distribuée également parmi les traitements de sorte que les mesures subséquentes n'étaient pas biaisées. Néanmoins, les semis avec le type 200 de tampons étaient significativement plus grands que pour le contrôle ou les traitements du type 100. Ces résultats montrent: (1) qu'il n'y a pas de substitution possible à une bonne technique de plantation pour assurer la survie des semis, et (2) que les tampons TREGRO de type 200 ont un effet bénéfique sur la croissance des semis même sous les conditions de sécheresse sévère connues en 1988.

Réhabilitation des terres forestières dans la vallée du Missouri au centre-ouest du Dakota du Nord

David J. Nilson

L'extraction minière de surface dans la vallée du Missouri nécessite l'enlèvement des forêts décidues des hautes terres. Ces forêts sont associées à des sites mésiques avec des drainages dendritiques qui coulent de façon intermittente vers le Missouri. Ces espaces forestiers ne sont pas seulement importants pour une variété d'espèces sauvages, mais aussi comme protection pour les cheptels durant les périodes climatiques extrêmes. Les méthodes utilisées pour rétablir des écosystèmes forestiers climaciques à la mine Glenharold sont discutées en incluant la remise en forme, le replacement du sol, les mélanges de plantes et les opérations de plantation et de gestion. Des données sur la survie, la diversité et la densité sont également apportées pour les surfaces établies entre 1978 et 1988. Pour fin de comparaison, ces données sont discutées en fonction de données amassées lors d'inventaires des forêts avant les activités minières à la fin des années 70 et début 80. La survie durant l'année de plantation et pour l'année subséquente est dépendante de la recharge en eau dans le sol durant l'hiver et pour les pluies de printemps et du début de l'été. Dans le même ordre d'idées, la préservation de l'humidité du sol par des pratiques de gestion appropriées est nécessaire pour promouvoir une revégétation réussie. Les données amassées à partir de surfaces avec de grands arbustes établis entre 1982 et 1984 montrent une survie initiale totale variant de 54 à 78%. La densité de tiges a augmenté de 150 à 375% à la fin de la troisième année de croissance. Les données amassées durant la saison de 1988 montrent des densités moyennes de tiges dans les terres forestières réhabilitées qui étaient de 60 à 70% des densités moyennes pour les communautés indigènes non perturbées.

Une évaluation économique de la technique de bioingénierie pour restaurer des communautés végétales indigènes

David G. Walker

Des techniques de bioingénierie (utilisation de matériel végétal vivant et indigène à des fins de revégétation et comme élément structural ont été évaluées à trois sites dans la région montagneuse de l'Alberta. Les diverses techniques de bioingénierie produisent un mélange de résultats variant d'un insuccès total à une réussite complète. L'humidité du sol, le temps d'installation (l'automne étant plus efficace que le printemps), la qualité du sol, les conditions climatiques, et la qualité du matériel végétal semblent tous des facteurs significatifs. Pour assurer le succès, la bioingénierie demande des travailleurs expérimentés, une inspection soigneuse, et des spécifications précises. Les techniques qui incluaient des plants déjà développés donnent un meilleur rendement économique pour l'établissement d'une végétation indigène.

INDUSTRIAL and URBAN SITES

Revégétation des haldes d'une usine de fertilisants phosphatés

Wendy E. Roberts Thorne et Richard D. Revel

Les usines de fertilisants phosphatés produisent des quantités énormes de résidus - cinq kilogrammes pour chaque kilogramme de fertilisant phosphaté produit. Un facteur majeur limitant la revégétation de ces haldes de gypse phosporé est le pauvre succès des programmes de revégétation, et le lent taux de revégétation naturelle. Cette étude présente les conclusions concernant les propriétés physiques et chimiques des haldes qui inhibent le plus la revégétation, et les résultats d'une étude en serre qui testait différents amendements et leur influence sur la croissance des plants. Des recommendations sont faites pour établir un ensemble d'amendements et de traitements physiques pour permettre l'établissement d'espèces végétales sur les haldes.

La reconversion des sites industriels et leur réhabilitation

D. Graveland et E. Osborne

Monenco Consultants travaille activement depuis près de 10 ans sur des projets de reconversion de sites industriels. Durant cette période, Monenco a publié un guide sur les aspects environnementaux de reconversion qui identifie le champs des activités impliquées dans la planification et l'exécution de reconversion d'un site industriel, sur la remise en ordre et la réhabilitation. Le guide montre dans ses grandes lignes une approche pas à pas qui nécessite l'implication et l'expertise d'une grande variété de disciplines. Ce texte souligne les problèmes, les questions d'intérêt et les défis auxquels les gens pratiquant la science du sol sont exposés à l'intérieur d'un cadre interdisciplinaire de projets de reconversion d'un site industriel.

Une évaluation technique et économique de la restauration des sites contaminés par les sulfures

S.A. Leggett, Jim Lore et S.L. Graves

La récupération des sites contaminés par le soufre est chose courante en Alberta depuis le début des années 80. Une variété de techniques sur la disposition hors-site ont été largement utilisées. Les techniques de récupération vont d'une utilisation importante du remplissage pour disposer du matériel contaminé par les sulfures jusqu'à des tentatives pour neutraliser et réhabiliter le matériel sur place. Les problèmes et les coûts de réhabilitation d'un site varient selon la localisation du site, ses conditions, et les techniques de récupération. Alors que la localisation et la condition du site sont des variables fixes, les choix des techniques de récupération peuvent influencer le succès des programmes de réhabilitation retenus. Ce texte fait l'examen des techniques actuelles utilisées pour la récupération et la réhabilitation, s'interroge sur les problèmes et les coûts associés avec chacune et donne des suggestions sur des alternatives disponibles pour de futurs projets de réhabilitation des sites contaminés par les sulfures.

Réhabilitation d'un bassin d'épandage industriel

C.B. Powter, L. Kryviak et G. Balko

En juin 1985, le Comté de Leduc en Alberta a approché la division de la réhabilitation du territoire d'Environnement Alberta pour réhabiliter un bassin d'épandage industriel à l'aide d'un programme de réhabilitation du territoire avec un fonds pour la conservation.

Le bassin d'épandage a été utilisé depuis 1976/77. La déposition de sous-produits industriels ou de déchets chimiques dans le bassin n'était pas permise, cependant le rejet n'était pas surveillé. Comme résultat, une accumulation de produits pétroliers a commencé à devenir problématique. Des échantillons de boues ont été soumis pour analyse des phénols et hydrocarbones polycycliques aromatiques, pour la production de composés volatiles, de métaux et de polluants prioritaires.

Les données ont indiqué que les boues contenaient des niveaux faibles de contaminants considérés comme modérément dangereux. Environnement Alberta a décidé de procéder en utilisant de nombreuses précautions pour protéger les travailleurs d'une exposition possible avec le contenu du bassin. Les travailleurs portaient des bottes de caoutchouc, des gants, des habits jetables, des masques respiratoires contre les poussières toxiques et la protection des yeux était assurée si il y avait de la poussière. Il n'y avait aucune prise de nourriture ou de boisson sur le site et aucun droit de fumer, et tous les véhicules étaient complètement lavés avant de quitter le site. Le site a également été entouré d'une clôture pour prévenir les entrées non autorisées.

La réhabilitation a débuté en novembre 1987. Une utilisation agricole a été sélectionnée comme la méthode économique la plus intéressante pour rendre les boues non dangereuses. Le Comté a apporté de l'aide en fournissant la main d'oeuvre et l'équipement pour les opérations agricoles. Les boues ont été étendues en surface sur les 3 ha du site et ce dernier a été mis en forme pour permettre le drainage dans un puisard. En mai 1988, après le gel et la subsidence du printemps, le site a été remodelé, cependant l'eau continuait encore à former un bassin en surface. En juillet, le site a été hersé pour faciliter le séchage du matériel en surface. Comme cela ne fonctionnait pas, un tracteur a été amené sur le site pour réétendre les boues. Le site a alors été fertilisé et cultivé. Une deuxième fertilisation et culture ont été faites à la fin d'août. Le site a été recultivé à la fin de septembre et les sols ont été échantillonnés pour une caractérisation chimique. Si les niveaux de substances organiques et de métaux sont encore inacceptables, le site aura encore une fertilisation et une culture durant 1989.

Dans la phase de planification, les caractéristiques chimiques des boues, et les précautions requises pour protéger les travailleurs, ont été considérées comme les obstacles majeurs au succès. Cependant, ce sont les caractéristiques physiques du sol créées par les boues qui ont causé les problèmes de réhabilitation les plus importants.

Relations entre les patrons de déposition, le sol et le développement de la végétation, et les concentrations en métaux lourds sur des haldes abandonnées

Jeanne C. Chambers, Roy C. Sidle et C. Val Grant

Les relations entre les patrons de déposition, le sol et le développement de la végétation, et les concentrations en métaux lourds ont été étudiées sur un bassin de résidus abandonné depuis 50 ans et localisé à 7200 pi. (2195m) dans les montages sud de Sangre De Cristo au Nouveau-Mexique. Les sédiments originaux proviennent d'opération de raffinerie de zinc et de plomb et sont caractérisés par de hautes concentrations en composés sulfuriques et un pH acide (2.2). Ils ont des quantités élevées en zinc, plomb, cadmium et cuivre. Depuis l'abandon, la déposition de sol au-dessus des résidus a suivi des patrons distincts. Des alluvions déposés à la base du bassin par un petit cours d'eau éphémère sont relativement humides et ont une biomasse végétale élevée. La végétation de cette région alluvionnaire inclue Salix spp. et Juncus balticus et est classée comme une prairie semi-humide. Ces sols d'alluvions ont des concentrations potentiellement phytotoxiques en zinc, plomb, cadmium et cuivre. Probablement, ces éléments ont été concentrés dans cette région par la végétation et par l'arrivée d'eau sur les sédiments originaux. Les matériaux alluvionnaires et éoliens déposés en amont de la base du bassin sont physiquement semblables à ceux des pentes adjacentes - sableux et faible en matière organique. La végétation sur cette surface est clairsemée et constituée d'espèces de site sec comme Bouteloua gracilis. Ces sols ont des niveaux de zinc, plomb, cadmium et cuivre qui sont plus élevés que ceux des sols environnants, mais qui sont plus faibles que ceux de la région de prairie semi-humide. Ils sont rarement phytotoxiques. Les résultats de cette étude indiquent que l'utilisation de prairies comme filtres pour les métaux lourds est grandement remise en question pour la réhabilitation de bassins de types semblables à cause de la concentration à long terme des métaux lourds dans les sols de surface.

La revégétation des pentes de dépotoir

Tom Hilditch

L'érosion des pentes de dépotoir ne provoque pas seulement la perte de sol, mais aussi un dommage potentiel de la surface de recouvrement au-dessus des détritus. Ce phénomène peut conduire à différents problèmes tels que;

- l'augmentation de l'infiltration de la pluie accélérant la percolation dans les détritus;
- l'augmentation de la mobilité des gaz et des filtrats du dépotoir;
- l'exposition des détritus; une attraction pour les animaux nuisibles;
- la réduction de l'esthétique et
- l'augmentation des coûts pour les travaux de réparation.

Dans une étude de trois années complétée pour le Ministère de l'Environnement ontarien (OMOE), tous ces problèmes ont été rencontrés. Ce programme de recherche incluait un travail en trois étapes;

- un survol de l'érosion des dépotoirs dans la province;
- l'identification des meilleures techniques de revégétation et
- l'établissement de lots de démonstration.

Ce texte se concentrera sur la présentation du produit final de l'étude de trois années, soit un manuel de revégétation. Le besoin pour un tel manuel a été renforcé durant des discussions avec les propriétaires de dépotoirs et les opérateurs et superviseurs à travers la province.

Les techniques existantes pour la revégétation de dépotoirs fermés diffèrent d'une place à l'autre. Il n'y avait aucune tentative pour donner une direction constante ou une application de labourage, de correction de sol, d'ensemencement et de techniques de maintenance. C'était l'état existant en dépit de l'observation de 88% des dépotoirs avec des problèmes d'érosion. De plus il n'y avait aucun effort de revégétation sur les deux tiers des sites rapportés par les responsables de l'OMOE. Sur le tiers restant, il y avait très peu de renseignements sur des applications autres que l'ensemencement hydraulique (sans labourage, tests de sol et maintenance ultérieure).

Ce texte présente les résultats du manuel de revégétation produit dans la dernière année de l'étude. Il est entendu de donner une référence facilement compréhensible et applicable pour n'importe quelle personne qui est impliquée dans la création et la maintenance de couverts végétaux sur des dépotoirs. Le profil du texte suit la table des matière du manuel d'assez près pour démontrer l'importance de la structure et de la composition d'un tel manuel pour la compréhension du matériel par l'utilisateur.

"Biorestauration": applications innovatrices d'une technologie établie

J. Bogart et J. League

L'utilisation agricole du territoire, longtemps un élément de base lors de projets de réhabilitation de raffineries et de terrains pétroliers, a été à l'origine de la biorestauration. La biorestauration a été étendue pour englober la réhabilitation des boues et de l'eau souterraine.

L'agriculture traditionnelle a subi des améliorations significatives qui ont produit des taux de mouvement qui ont des magnitudes plus grandes que celles atteintes antérieurement.

MoTec Inc., un contracteur en biorestauration, a produit des développements innovateurs en biotechnologie. Ceux-çi ont étendu la variété de composés utilisables en biotechnologie et les taux de dégradation réalisés. Ils incluent une technologie brevetée, une digestion de contact liquides-solides, des techniques agricoles améliorées, et l'utilisation de matériel dans la réparation de sol et d'eau souterraine contaminés.

MoTec a restauré des milieux contaminés contenant de l'huile et des graisses, des hydrocarbures de pétrole, du créosote, du pentachlorophénol, des pesticides, des BPC et des rejets industriels. Les candidats idéals pour la restauration incluent les boues de forage, les résidus de production et d'huile de shale. Des sites de déversement ont également été restaurés avec succès.

La biorestauration est pratique pour les boues, les sols contaminés, l'eau souterraine contaminée, l'eau de transformation, et les boues de transformation des systèmes de traitement des eaux usées industrielles. La biorestauration a été démontrée comme étant techniquement faisable. Elle a été approuvée par plusieurs agences de règlementation. Elle est économiquement efficace, avec des prix unitaires souvent à moitié plus bas que les méthodes alternatives.

PROBLEMS and SOLUTIONS

Design et performance de canaux et déversoirs incorporant un renforcement par des revêtements.

G. I. Dodson

Les nattes des produits Enkamat ont apporté un renforcement à la végétation pour le contrôle de l'érosion depuis 1975. La sparterie a donné ses preuves dans les designs de canaux, déversoirs, pentes et berges.

Le design des déversoirs fait l'objet d'un intérêt récent dû à un besoin important apporté par l'ingénierie des barrages. Des déversoirs incorporant les produits Enkamat ont été largement évalués par des gouvernements indépendants et des groupes de recherche privés aux Etats-Unis, au Canada et en Europe. Le système Akzo Industrial a pu de bénéficier de ces études.

Par ces efforts de recherche fortement correlés, Akzo a été capable de développer un standard de performance pour le design des déversoirs d'Enkamat. Les produits Enkamat donnent une alternative plus économique aux revêtements des déversoirs plus rigides et moins esthétiques.

Le facteur de design primaire à considérer pour un déversoir Enkamat est le stress maximum de cisaillement que le revêtement peut supporter. Pour une natte végétale Enkamat 7010 le cisaillement maximum devrait être de 5 lbs/pi^2, alors que pour l'Enkamat 7020, il est de 8.0 lbs/pi^2. L'équation pour le stress de cisaillement est:

Stress de cisaillement = (poids unitaire de l'eau >62.4 lbs/pi.3<) x (rayon hydraulique du canal) x (la pente du canal).

Dans les conditions où la largeur du canal serait 5 fois plus grande que la profondeur de l'écoulement, la profondeur devrait être substituée au rayon hydraulique dans le calcul.

En plus des caractéristiques hydrauliques du déversoir, le concepteur du système devra aussi considérer le type de sol et le couvert végétal spécifique. Les services locaux de conservation du sol sont historiquement de bonnes sources pour de telles informations.

Système de disposition des résidus d'enrichissement à la mine de bauxite de Trombetas

Reginaldo Pedreira Lapa et Fernando Valentim Carraresi

Mineracao Rio do Norte (MNR) est une compagnie créée en 1967 dont les actionnaires sont CVRD (46%), ALCAN (24%), CBA (10%), BILLITON (10%), NORSK HYDRO (5%), et Reynolds Aluminium (5%).

Son opération, localisée dans la région de l'Amazone, a commencé en 1979. Depuis ce temps, les résidus d'enrichissement ont été disposés près du lac Batata. le volume annuel de résidus est de près de 18 millions m^3 avec un contenu solide de 7-9%. Cela a causé un problème écologique très important. Dès le début de l'opération, la MNR et les autorités de protection environnementale ont décidé qu'une méthode plus écologique pour la disposition des résidus devrait être établie.

En 1982, les consultants Bromwell and Carrier Inc (Lakeland - Florida), ont commencé des tests d'épaississement et de pompage sur les résidus déposés dans le lac Batata. Des tests pilote dans un petit bassin de déposition ont été commencés en 1984.

Comme résultat à ces tests, il a été proposé de déposer les résidus épaissis dans les endroits déjà exploités. Ce texte décrit les équipements industriels, leur impact environnemental sur la région amazoniène, les études pour la disposition des résidus dans les endroits déjà exploités, la construction de fossés par l'utilisation de dragage, le plan de disposition des résidus et finalement la réhabilitation des surfaces de disposition.

Ce projet a été réalisé depuis septembre 1986 et le nouveau système de disposition des résidus deviendra opérationnel durant la seconde moitié de 1989.

Tendances récentes dans la réhabilitation des mines de phosphate aux Etats-Unis

Wayne R. Marion

L'extraction minière du phosphate a lieu dans plusieurs régions des Etats-Unis, incluant des portions de la Floride, de la Caroline du Nord, du Tennessee, de l'Idaho, du Montana, de l'Utah, du Wyoming et de la Californie. La Floride et la Caroline du Nord combinées comptent pour environ 85%, les états de l'ouest pour 10%, et le Tennessee pour 5% en matière de production totale de phosphates aux Etats-Unis. Comme prévu, le phosphate est extrait selon différentes conditions écologiques et physiques dans chaque état et cela conduit à des différences dans les exigences de réhabilitation et dans les attentes. Egalement, le climat politique associé à l'extraction du phosphate est extrêmement variable d'un état à l'autre et cela s'est reflété dans les règlements de réhabilitation. La Floride a les standards environnementaux et les règlements de réhabilitation les plus rigoureux de tous les états mentionnés, avec la Caroline du Nord, les états de l'ouest et le Tennessee ayant respectivement des restrictions moins rigoureuses et moins de règlements de réhabilitation. Ce texte compare et met en contraste les règlements de réhabilitation et indique les changements dans les tendances de réhabilitation pour chacun des états sur une période de cinq ans, 1983-88. En Floride, des revisions des règlements de réhabilitation pendant cet intervalle ont résulté en des changements d'une emphase première où le focus était dirigé sur le ré-établissement des sites humides vers une emphase plus récente sur le redéveloppement des patrons de drainage et sur la réhabilitation des forêts des hautes terres. Les changements de réhabilitation dans les autres états ont été plus subtils, avec des utilisations subséquentes du territoire dictant souvent les exigences de réhabilitation. Aussi, la discussion portera sur des implications et des recommendations sur les habitats de la faune sauvage et sur la réhabilitation des systèmes naturels dans chaque état.

Exploitation minière et réhabilitation de terres agricoles de premier choix à l'ouest du Dakota du Nord

Joe Friedlander

La réhabilitation de terres agricoles est exigée par la Loi de 1977 sur le contrôle des opérations minières de surface et de la réhabilitation. La compagnie "The Coteau Properties" opère une mine de lignite dans l'ouest du Dakota du Nord, et est la seule compagnie dans l'ouest semi-aride à faire de l'exploitation minière et à réhabiliter des larges superficies de terres agricoles de premier choix. Les caractéristiques des terres agricoles de premier choix dans l'ouest du Dakota du Nord ne sont pas adressées par les exigences règlementaires fédérales, et s'opposent avec les exigences d'Etat pour la réhabilitation de toutes terres de cultures au Dakota du Nord. Ce conflit résulte en une perturbation environnementale additionnelle non nécessaire durant l'opération minière, et augmente les coûts de réhabilitation pour l'opérateur de la mine. Les opérations de réhabilitation à la mine "Freedom" sont décrites. Des changements recommandés pour les règlements sur les terres agricoles de premier choix et sur les interprétations des règlements existants mettront en valeur la réhabilitation pour toutes les terres de culture de l'ouest du Dakota du Nord, autant celles de premier choix que les autres.

Geological and environmental considerations in abandoned underground mine re-use and rehabilitation

Daniel J. Boivin

Much attention worldwide has been devoted to the restoration of abandoned surface mine sites, emphasizing reclamation and revegetation techniques to restore the land to environmentally acceptable standards. This paper documents various possibilities for conversion of abandoned underground mines. Creative re-use could be made of cavities remaining after mining operations are complete. The possibilities and constraints offered by these excavations are discussed, with specific attention to geological and environmental considerations. Among the options used around the world are: the conversion of old mines as water or oil reservoirs; dry goods storage; plant nurseries; underground farms for vegetables and mushrooms; tourist attractions; and conversion to other industrial uses.

Un survol de deux décennies de règlements sur l'extraction charbonnière de surface et la réhabilitation au Dakota du Nord

William E. Dodd, James R. Deutsch, Edward J. Englerth, Nirander M. Safaya

Au Dakota du Nord, la production de charbon (lignite) et l'utilisation de méthodes ont changées considérablement depuis l'ouverture de la première mine commerciale en 1873. L'extraction de surface a débuté en 1919 et est devenue la méthode exclusive de récupération du charbon jusqu'en 1966. Le nombre de mines de charbon, principalement pour les petites extractions souterraines, a décliné de 320 en 1941 jusqu'à 10 mines de surface actuellement actives. Mais la production de charbon a augmenté continuellement, atteignant 28 millions de tonnes en 1988. Aujourd'hui, 78% de la lignite du Dakota du Nord est utilisée pour la production d'électricité, 20% pour la production de gaz synthétique, et le restant comme combustible domestique et commercial.

La règlementation environnementale de l'industrie de la lignite du Dakota du Nord a commencé en 1969 quand l'état a passé sa première loi sur l'extraction minière et la réhabilitation. Les exigences de réhabilitation étaient limitées au revêtement et à l'ensemencement des buttes de résidus. Depuis ce temps, les lois de réhabilitation et les règlements ont augmenté significativement leur visée et leur rigueur, principalement à cause des changements de la loi de 1975 et de la promulgation de l'acte fédéral sur le contrôle et la réhabilitation des opérations minières de surface en 1977 (P.L. 95-87). Le propos de ce texte est de démontrer les impacts sur la qualité de l'environnement et l'avenir de l'industrie charbonnière du Dakota du Nord.

Considérations économiques affectant la restauration d'habitat dans l'industrie minière du phosphate en Floride

Timothy P. King et Wayne R. Marion

L'exploitation minière du phosphate constitue une proportion relativement petite de l'activité minière au monde, mais les produits phosphatés sont nécessaires comme fertilisants, produits chimiques industriels et suppléments alimentaires pour les animaux. Où l'activité minière a lieu, l'excavation de surface cause une perturbation majeure des sols, des patrons de drainage, des communautés végétales et animales. Les standards de restauration et de revégétation sont extrêmement variables de part le monde; la situation en Floride représente probablement un des systèmes de réhabilitation au monde parmi les plus restrictifs et progressifs. En Floride, la réhabilitation de chaque acre de terre perturbé par l'activité minière est exigée depuis 1975 et plusieurs options se sont développées suite à l'amélioration du système depuis les 13 dernières années. Les aspects économiques du marché mondial pour le phosphate, la variation des exigences pour réhabiliter le territoire, et les coûts relatifs pour plusieurs techniques de réhabilitation ont fréquemment imposé un design au paysage subséquent, une composition de la communauté végétale et une utilisation anticipée du territoire. Typiquement, le moins cher a été considéré comme la meilleure option; cela peut ne pas être adéquat quand des éléments et des fonctions uniques sont considérés pour ces écosystèmes restaurés. Ce texte apporte une détermination et une évaluation de l'information existant en regard des aspects économiques de la réhabilitation reliée au phosphate et de l'apparence finale de ces paysages miniers. Les incitations au règlement et l'opportunité de faire un gain financier au delà des coûts de restauration sont vues comme les principaux déterminants pour l'utilisation post-restauration du territoire. La possibilité d'augmenter la restauration des habitats par la promotion d'une utilisation récréative du territoire comme motivation financière est soulignée. Plusieurs exemples sont donnés montrant des options pour augmenter la valeur des habitats avec très peu ou pas de coût additionnel de restauration.

Réhabilitation du site minier de Rum Jungle

J.W. Bennett, D.K. Gibson, J.R. Harries, G. Pantelis,
A.I.M. Ritchie, T.J. Verhoeven et J. Alcock

L'oxydation des résidus de pyrite de la mine d'uranium et de cuivre de Rum Jungle dans le territoire Nord de l'Australie, a causé une pollution de la rivière locale par l'acidité et les métaux lourds. L'extraction minière et la transformation du minerai ont débuté sur le site minier en 1952 et se sont poursuivies jusqu'en 1971 lors de l'abandon. Un projet de réhabilitation a été initié en 1982 avec des travaux sur le site terminés en 1986, et avec un programme de surveillance et de maintien jusqu'en juin 1988. Le projet était géré par le gouvernement du territoire du Nord et les fonds donnés par le gouvernement du commonwealth australien.

La réhabilitation incluait:

- le traitement de l'eau dans deux tranchées d'inondation et la redirection d'une portion du flux de la rivière locale dans celles-çi;
- l'enterrement des résidus et du matériel d'un amoncellement expérimental dans une troisième tranchée, et;
- la remise en forme, le recouvrement et la revégétation des dépôts de la gangue.

Les coûts du projet jusqu'à juin 1986 étaient de $(AUD) 18.6 millions avec un budget supplémentaire de $(AUD) 350,000 pour la surveillance et la maintenance.

La surveillance a montré que la réhabilitation a réduit l'infiltration d'eau dans les dépôts de débris rocheux à 3% des précipitations et le taux d'oxydation de la pyrite à un niveau en-dessous du seuil de la détection. Les quantités et les concentrations de cuivre dans l'eau de la rivière ont été réduites. Par exemple, la concentration maximale quotidienne de cuivre pendant la saison humide en 1986-87 est descendue à 3.4 mg/L comparativement à 182 mg/L en 1982 et une quantité de 6 à 23 tonnes même si la décharge totale d'eau en 1986-87 était plus élevée d'environ 30%.

Il n'y a eu aucun changement observable dans la qualité de l'eau souterraine. Nous avons développé des modèles de flux d'eau souterraine et de transport des contaminants qui montrent que cela prendra des décennies avant d'avoir des changements significatifs dans la qualité de l'eau souterraine.

SODIC and SALINE MATERIALS

Les effets de l'épaisseur du sous-sol sur la productivité et l'eau du sol lors de la revégétation de déchets miniers sodiques.

T. Oddie, E. Osborne, D. Graveland et L. Panek

Les déchets miniers sodiques perturbent la croissance des plantes et empêchent les chances de revégétation des surfaces minières. Une expérience conjointe entre le gouvernement et l'industrie charbonnière a été faite près de Highvale en Alberta pour déterminer des épaisseurs de sous-sol qui conviennent (0, 55, 95, 135, 185 et 345 cm sous 15 cm de sol de surface) pour revégéter des déchets miniers sodiques et maximiser la production d'une récolte céréalière (Hordeum vulgare L.) ou d'un mélange fourrager composé de Medicago sativa L. et Bromus inermis Leyss.

Les productions d'orge et de fourrage étaient plus basses pour le traitement de 0 cm de sous-sol par rapport aux autres traitements. Les productions pour les deux récoltes ont augmenté lors que l'épaisseur du sous-sol augmentait à 55 cm. Il y avait une tendance vers des productions optimales pour le traitement de 95 cm, mais la différence entre 55 et 95 cm n'était pas significative. Le placement de 55 à 95 cm de sous-sol avec 15 cm de sol de surface semble suffisant pour redonner à la productivité post-minière un potentiel équivalent aux terres agricoles environnantes.

La profondeur des racines pour le mélange fourrager augmentait comme l'épaisseur du sol augmentait, alors que les accroissements pour la récolte céréalière n'étaient généralement pas significatifs. La zone racinaire moyenne s'étendait à environ 85 cm sous l'orge et 185 cm pour le mélange luzerne et brome. La moyenne saisonnière de l'eau du sol dans la partie racinaire effective augmentait généralement sous l'orge et diminuait sous la luzerne et le brome avec le temps. Une utilisation plus faible de l'eau du sol par la zone racinaire de l'orge contribuait à des accumulations de l'eau au-dessus de l'interface sous-sol et déchets miniers. Des fourrages permanents semblent plus efficaces pour réduire les accumulations d'eau au-dessus de l'interface et apportent des chances de revégétation pour les déchets miniers sodiques.

Utilisation de la cendre comme amendement sur des déchets sodiques

S. Landsburg

Le but de ce projet était d'évaluer l'utilisation de la cendre comme amendement physique sur des déchets sodiques. Le dépôt sodique était localisé à la mine Vesta près de la ville de Halkirk au centre-est de l'Alberta. Les objectifs de cette étude étaient de déterminer les meilleurs taux et méthode d'application de la cendre sur le déchet sodique de façon à réduire les effets d'un excès de sodium et de permettre la croissance végétale.

Les places-échantillons ont été établies selon un design au hazard. Les trois profondeurs de cendres testées étaient de 10, 20, et 30 cm. La cendre a été appliquée à la surface des déchets en utilisant un tracteur D8 et était incorporée avec du matériel spécialisé (disque laboureur, sous-solage etc.). Une quatrième méthode laissait la cendre en surface comme une couverture.

Chaque année les sols des sites ont été échantillonnés par sauts de 15 cm jusqu'à une profondeur maximum de 90 cm. L'humidité du sol a été mesurée par sauts de 15 cm jusqu'à une profondeur de 120 cm. Des mesures de productivité et de résistance de sol ont également été prises. Les variables du sol mesurées sur une période de trois ans (1983 à 1985) incluaient le pH, la conductivité électrique, le pourcentage de saturation, le calcium soluble, le magnésium, le sodium et les sulfates,la matière organique et le bore. Les variables de plantes mesurées incluaient les pourcentages d'azote, de phosphore, de potassium, de calcium, de magnésium et de bore.

Les résultats montraient que le meilleur taux de cendres était de 30 cm et que la meilleure méthode d'incorporation était le sous-solage. Les deux ont augmenté les mouvements d'humidité vers le bas et diminué les valeurs de résistance du sol ce qui permet l'écoulement, la germination et la croissance racinaire. Le taux de 30 cm a également amélioré l'aspect chimique des 15 cm en surface des déchets et a augmenté la productivité. Les productivités utilisant les taux de 10 et 20 cm étaient en-dessous de celles reportées par les propriétaires locaux, alors que les productivités pour le 30 cm étaient supérieures.

Toutes les méthodes plus les taux de 20 et 30 cm ont produit des niveaux toxiques de bore disponible dans le sol. Les concentrations du sol n'étaient pas visibles dans aucun des symptômes de toxicité des plantes.

Réponse du maïs à un labour profond sur une surface minière transformée en terre agricole de première qualité en Illinois.

R.E. Dunker, I.J. Jansen et S.L. Vance

L'effet de l'utilisation d'un appareil de labourage profond (Kaeble-Gmeinder TLG-12) sur la croissance du maïs sur des sols miniers reconstitués a été évalué à la mine Norris de la Consolidation Coal Company au centre-ouest de l'Illinois durant les années 1985-86. Deux sols miniers, un étant fait de 45 cm de sol de surface replacé sur les déblais régalés et l'autre étant composé des déblais seulement, ont été évalués avec et sans le traitement du TLG-12. Un sol dit "Sable" a été utilisé comme élément de comparaison pour une surface non minière. L'utilisation du TGL-12, qui a une profondeur effective de labourage d'environ 75 cm, était efficace en diminuant significativement la résistance au pénétromètre dans les segments de 23-46 et 46-68 cm comparativement aux traitements sans labourage pour les deux sols miniers. La réponse de la productivité du maïs au TGL-12 était significative autant en 1985 et 1986 quoique l'ampleur de la réponse était plus grande en 1985, une année de stress climatique élevé. Des différences significatives pour les dates de pollinisation, les % de tiges stériles, et les niveaux de tension d'humidité du sol à certaines profondeurs, étaient observées entre les traitements labourés et non labourés. Les productivités moyennes du maïs pour les deux années pour le traitement avec sol de surface et le traitement de déblais seulement avec le TGL-12 étaient comparables aux productivités pour le sol "Sable" non minier alors que les sols miniers non labourés ne l'étaient pas. Aucune réponse de productivité suite au replacement de sol de surface pour chacun des traitements de labourage n'ont eu lieu autant en 1985 que 1986.

Projet de reconstitution du sol "Battle River": Résultats de cinq années de l'expérience de sol Torlea

L.A. Leskiw et N.M. Finlayson

Le projet de reconstitution du sol de la rivière Battle, comportant 4 expériences, a été surveillé intensivement pendant 5 ans, de 1982 à 1986. Les buts étaient de déterminer les méthodes les plus efficaces pour réhabiliter des terres minières en utilisant différentes profondeurs et qualités de matériaux du sol.

Ce texte porte spécialement sur l'expérience de sol Torlea qui était fait pour évaluer les méthodes d'amélioration de la sodicité suivantes:

1. enlèvement de l'horizon sodique B;
2. mélange de l'horizon sodique B et de l'horizon C avec calcium;
3. application de gypse;
4. application de cendres riche en calcium.

En respect des rendements agricoles il n'y avait pas de croissance sans la présence de sol de surface ou de sous-sol au-dessus des déblais; une pauvre croissance avec le sol de surface sur le déblai; une bonne croissance avec le sol de surface sur le sous-sol sur le déblai. Des mélanges de l'horizon de sous-sol et des variations en profondeur n'ont pas donné de différences de productivité statistiquement significatives; cependant, des sous-sols plus profonds tendent à donner un meilleur rendement. Des amendements se sont avérés très bénéfiques; la cendre a surpassé le gypse et les places de contrôle. Les places traitées au gypse donnaient des rendements presque plus élevés que pour les places de contrôle. Les rendements ont décliné avec le temps à cause du vieillissement du labourage et des différences de précipitations.

La qualité du sol exprimée par la salinité et la sodicité étaient plus ou moins correlée avec les rendements selon que les meilleurs rendements s'identifiaient aux meilleures qualités de sol. Le sol de surface au-dessus du sous-sol est mieux mais les niveaux de salinité et de sodicité restent modérés à élevés dans le sol de surface, respectivement. Les sols de surface et les sous-sols les plus élevés se sont améliorés depuis la reconstitution et les sous-sols les plus bas se sont dégradés indiquant ainsi un écoulement dans le profil supérieur et une accumulation de sels en profondeur. Ces changements étaient plus prononcés durant les premières années que pour les dernières, indiquant que les conditions peuvent se stabiliser, au moins durant les sécheresses plutôt que lors de la température normale. L'addition de cendre au sol de surface a été très bénéfique pour améliorer la qualité du sol.

Revégétation de déblais sodiques au nord-ouest du Dakota du Nord

Louis A. Ogaard

Des sites miniers abandonnés de charbon ont été revégétés dans les Comtés de Burke, Divide et Williams au coin nord-ouest du Dakota du Nord. Aucun matériel de croissance adéquat était disponible. Des échantillons des déblais indiquaient des ratios d'absorption de sodium dans une amplitude de 21 à 38 et des valeurs de conductivité électrique entre 5 et 8. Les sites ont été fertilisés à un taux de 70 lbs/acre d'azote et de 20 lbs/acre de phosphore. le mélange de graines était composé de Agropyron smithii, Agropyron trachycaulum, Agropyron dasystachyum et Melilotus officinalis. Un paillis de paille a été appliqué à trois tonnes par acre et attaché à la surface des déblais. La germination au site du Comté de Williams, qui a été semé en juillet, a été excellente. Les sites des Comté de Burke et Divide ont été semés trop tard dans l'année pour un établissement végétatif. Les trois sites seront examinés durant la saison de croissance de 1989 pour le recouvrement au sol, la productivité et la composition spécifique.

Résidus salins - Le défi ultime en réhabilitation de milieux salins

Bob Hart

Le potassium, un des trois éléments nutritifs essentiels pour la croissance des plantes est fourni comme fertilisant par la transformation et l'enrichissement d'évaporites riches en potassium comme la potasse. Le Canada, principalement la Saskatchewan, produit environ 20% de la production mondiale et a presque 70% du minerai récupérable dans le monde. Des 80 opérations à travers le monde, la plupart reposent sur des techniques minières standards et disposent leurs résidus en surface. Les boues d'enrichissement qui comprennent au moins 60% de minerai de meilleure qualité comme en Saskatchewan, sont dominées par NaCl.

La contamination de surface et de l'eau souterraine par l'eau salée, originant de l'entreposage en surface des résidus et la précipitation des sels, est le problème environnemental principal auquel fait face l'industrie. Quoique chargée de problèmes, l'industrie a eu certains succès pour retenir l'eau salée et limiter l'impact environnemental. Des tentatives de réduction seront discutées.

Malheureusement, peu de considération a été donnée à l'abandon et à la réaffectation des amoncellements de résidus de potasse. Si les techniques minières demeurent les mêmes, durant le temps où les réserves de la Saskatchewan seront utilisées, les 10 amoncellements de résidus actuels comprenant 250 millions de tonnes de sel augmenteront au nombre de 200 avec 20 000 millions de tonnes pour une superficie de 1600 km^2. L'impact sur la ressource en eau souterraine de la Saskatchewan sera désastreux à moins que des méthodes alternatives de disposition des résidus ne soient développées ou que les résidus puissent être isolés de l'environnement.

A la lumière des expériences de réhabilitation des résidus de potasse à travers le monde, des options de réhabilitation et de réaffectation, et des besoins en recherche seront considérés.

Les effets d'amendements en gypse phosphaté et en chlorure de magnésium sur des résidus miniers abandonnés de bentonite

S.C. Smith et D.J. Dollhopf

La réhabilitation de déchets miniers abandonnés de bentonite est difficile à cause de la salinité et de la sodicité élevées, et d'un haut contenu d'argile smectique. Ces résidus qui se dispersent facilement quand ils sont mouillés donnent une infiltration réduite de l'eau et la formation de croûtes de surface imperméables. Des amendements chimiques se sont avérés efficaces pour améliorer les propriétés physicochimiques inhérentes à ces résidus abandonnés. Des places-échantillons ont été mises sur le terrain pour vérifier l'efficacité d'une eau salée de gypse phospaté et de chlorure de magnésium comme amendements aux résidus. Ces matières sont des sous-produits industriels de faible coût.

L'analyse des constituents chimiques des amendements indiquait que le gypse phosphaté contenait 82.1% de $CaSO_4 . H_2O$ et que le chlorure de magnésium avait 40.8% de $MgCl_2$. Le gypse phosphaté était enrichi d'argent, de cadmium et de sélénium. Cependant, l'incorporation de l'amendement a résulté dans une dilution de 110:1 pour prévenir les accumulations d'éléments traces.

Après deux saisons de croissance, l'application de ces amendements a résulté dans une réduction des mesures de salinité (SAR et % de saturation) et une amélioration de l'infiltration d'eau. L'amélioration des paramètres physicochimiques du sol minier indique qu'un médium de croissance plus désirable pour les plantes est en train de se développer.

Comparaison de résidus miniers sodiques et non sodiques en regard de la résistance du sol en fonction d'une humidité du sol variable

D.J. Thacker et R.L. Johnson

Les résidus miniers de la formation géologique de Luscar dans les montagnes rocheuses de l'Alberta ont été analysés en matière de résistance du sol à des tensions d'humidité de 1/3, 1, 3 et 15 bars. Les résidus miniers de cette formation géologique incluent des matériaux non salins à texture grossière et des matériaux salins à texture fine. Les résidus miniers utilisés dans l'expérience ont été sélectionnés pour inclure une grande variété de textures.

Des sous-échantillons de chacun des résidus sodiques ont été délavés de façon à évaluer l'effet du sel et du sodium sur la résistance du sol dans des échantillons semblables. Les filtrats des résidus salins ont été utilisés pour saliniser les sous-échantillons de résidus non salins afin de permettre une détermination similaire. Après cinq cycles de mouillage et de séchage les résistances des résidus ont été mesurés à des tensions d'humidité de 1/3, 1, 3 et 15 bars avec un pénètromètre en cône. Trois répétitions ont été utilisées pour chaque série de mesures. Les résultats sont présentés.

Améliorations en matière de restauration des sites de cendres

H. Insam

Un projet de restauration a été conduit sur le dépôt de cendres de Braunschweigische Kohlebergwerke situé à Helmstedt en Allemagne de l'Ouest. Les problèmes rencontrés étaient un pH élevé et des concentrations en sels élevés en relation avec une mauvaise stabilité physique du substrat. Plusieurs combinaisons de fertilisants, composts et amendements divers ont été testés en vue d'améliorer la croissance végétale et les conditions microbiologiques (biomasse et activité biologique). Plus particulièrement, l'usage de compost dérivé d'écorce et d'un produit fabriqué à partir de mycelium mort a été très performant. L'addition de divers amendements contenant des minéraux argileux et certains composés à base de sucre a considérablement amélioré les paramètres étudiés. Ces effets sont peut être liés à une réduction de la disponibilité de certains composés toxiques ou à une réduction locale du pH.

SOILS and OVERBURDEN

Variabilité des propriétés chimiques et physiques de déchets miniers remis en forme

Gary A. Halvorson

La variabilité des propriétés chimiques et physiques de déchets miniers remis en forme a été mesurée sur quatre sites dans l'ouest du Dakota du Nord. L'objectif principal de cette étude est de prédire les propriétés d'une surface remise en forme à partir de données sur la gangue originale. Les échantillons ont été pris selon un patron carré étendu de façon à ce que la variabilité dans une petite région puisse être comparée à celle d'une grande surface. Les dimensions d'une surface échantillonnée variaient de 10 m^2 à 55 ha. Les propriétés des déchets mesurées incluaient le pH, la conductivité électrique, le calcium, le magnésium et le sodium solubles, le ratio d'adsorption en sodium et le pourcentage en sable, silt et argile. La variabilité dans les propriétés du sol mesurée par un coefficient de variation pour la plus petite surface était de 50-70% de la plus grande surface. Des difficultés ont été rencontrées pour assortir la gangue originale avec les propriétés des déchets remis en forme parce que le degré de remise en forme de la surface après l'extraction minière n'était pas prévisible.

Caractéristiques physiques et chimiques des résidus d'une usine de charbon au sud-ouest de la Virginie

B.R. Stewart et W.L. Daniels

Les résidus du charbon sont difficiles à revégéter à cause de leur potentiel élevé d'acidité, de leur contenu en fragments grossiers, de leur faible capacité de rétention d'eau, de leur basse fertilité et d'autres problèmes. Peu est connu au sujet de leurs propriétés, particulièrement en regard du potentiel de revégétation. Il y a actuellement plus de 4000 ha d'amoncellements de résidus charbonniers abandonnés, et plusieurs milliers d'hectares de dépôts de résidus actifs dans le sud-ouest de la Virginie seulement. Cette étude a été entreprise pour déterminer les propriétés physiques et chimiques de ces matériaux. Des échantillons de 27 amoncellements de résidus, variant en âge de 1920 jusqu'à maintenant ont été amassés pour en faire la caractérisation. Les propriétés physiques et chimiques sélectionnées variaient largement parmi les échantillons. Les valeurs de pH variaient de 8.3 à 3.0, et les amoncellements les plus âgés avaient les valeurs de pH les plus basses comparativement aux plus récents. Les saturations en bases s'étendaient de 100% à 1% et comme prévu, étaient fortement corrélées avec les valeurs de pH. La conductivité électrique était plus élevée dans les résidus plus jeunes. La valeur de conductivité électrique la plus élevée observée était de 5.8 mmho/cm ce qui est suffisant pour affecter la croissance des plantes sensibles aux sels. La moyenne des fragments grossiers (>2mm) de ces matériaux était de 60%. La texture moyenne des particules fines (<2mm) était un loam sableux avec 15% d'argile. La différence moyenne de rétention en eau, entre 0.1 bar et 15.0 bar de tension d'humidité, sur la fraction des particules fines était de 0.136 g d'eau/g de sol. Ces valeurs de rétention d'humidité sont très basses comparativement à celles des sols naturels, particulièrement en regard du contenu élevé en fragments grossiers. D'autres propriétés physiques, chimiques et minéralogiques importantes pour les résidus seront discutées, et reliées au potentiel de réhabilitation de ces matériaux.

Altération de la sidérite ($FeCO_3$) d'une halde de lignite

N.M. Frisbee et L.R. Hossner

Lors des déterminations de la balance acide/base pour du matériel de remblai, il y a des erreurs substantielles par l'utilisation de procédures analytiques courantes pour détecter la production d'acide par les haldes. Il semble y avoir une corrélation entre la présence de sidérite et les interférences lors de la détermination du potentiel de neutralisation (PN) et du potentiel d'acidité (PA) du matériel des haldes.

Nous avons étudié l'altération de la sidérite d'une halde de lignite du Texas. Les effets du gaz carbonique et de l'air sur la vitesse d'altération de la sidérite ont été déterminés.

Des nodules de sidérite altérée ont été placés dans des contenants et couverts avec de l'eau déionisée ou avec un tampon de pH=3. Un courant continu de gaz carbonique, d'oxygène, ou d'air était envoyé dans les échantillons.

Des tranches d'échantillons ont été prises et examinées au microscope électronique et pétrographique. Les tranches étaient prises à des intervalles mensuels et examinées pour détecter la croissance ou le changement dans les anneaux d'oxydation couvrant les nodules.

De la sidérite fraîche a été utilisée pour les titrages du pH pour déterminer les taux de réaction des particules de dimensions spécifiques. La sidérite était écrasée puis tamisée dans des passoires de plusieurs dimensions, puis congelée à sec et emmagasinée jusqu'à l'utilisation. L'échantillon était titré avec de l'acide sulfurique pour maintenir un pH de 3.

Potentiel de revégétation pour le matériel de la gangue des mines de charbon de Kittanning

J.C. Sencindiver, N.C. Thurman et R.J. Fugill

Les filons de charbon de Kittanning en Virginie ont généralement des gangues produisant de l'acidité. L'extraction minière de ces filons produit généralement un drainage acide et des problèmes avec la revégétation à moins qu'un sol de surface soit replacé. Même si les matériaux acides sont communs, des matériaux de gangue non acides ou alcalins peuvent être présents à certains sites. Certains de ces matériaux peuvent être meilleurs pour la revégétation que le sol de surface original. Deux études ont été conduites pour évaluer le potentiel de revégétation des matériaux de la gangue à Kittanning. Dans la première étude, des colonnes mesurant 30 cm de diamètre par 91 cm de long ont été remplies avec les résidus seulement, avec les résidus et le sol de surface, et avec un mélange des résidus en plus du sol de surface et de pierres concassées. Tous les matériaux ont été chaulés et fertilisés au besoin, semés avec *Festuca arundinacea* et *Lotus corniculatus*, et placés à l'extérieur. La croissance végétative et le couvert de surface ont été évalués après deux saisons de croissance. Les résidus recouverts de sol de surface avaient un couvert de surface moindre que pour tous les autres traitements. Les propriétés chimiques du sol de surface étaient généralement inférieures que pour les autres matériaux. La seconde étude était conduite sur une surface minière où un tissu PVC a été placé au-dessus du matériel acide. Le tissu était recouvert d'un sol de surface de 35 à 100 cm ou par un substitut au sol de surface (roche-mère concassée). Le tout a été chaulé, fertilisé et semé avec *Festuca arundinacea*, *Lotus corniculatus*, *Trifolium hybridum* et *Trifolium pratens*. Le couvert de surface pour le sol et le substitut de sol était évalué pour deux saisons de croissance. Le couvert de surface était substantiellement mieux sur le sol que sur le substitut. Cette différence était reliée aux propriétés acides de la roche-mère utilisée comme substitut. Ces études indiquent une certaine variabilité dans les matériaux de la gangue à Kittanning. Un bon programme d'analyse de la gangue avant les opérations minières est requis pour déterminer quels matériaux de la gangue sont utilisables comme substituts de sol de surface.

Etude d'une halde de la mine Highvale et planification de la réhabilitation

A. Schori, W.J. Hastie et C. Wenzel

Une étude détaillée d'une halde à la mine Highvale au centre de l'Alberta a été conduite entre 1984 et 1986. Des données chimiques et physiques pour des échantillons forés ont été utilisées pour: décrire les propriétés des unités principales de la halde; préparer des carottes de forage et des sections stratigraphiques; et déterminer la localisation et la profondeur de la halde. Les matériaux de la halde étaient évalués pour leur convenance à la revégétation. Ce texte décrit comment l'information des carottes de forage a été amassée et souligne comment cette information peut être intégrée pour maximiser l'efficacité de la manipulation des matériaux et atteindre un succès dans la revégétation.

Approche courante de réhabilitation des sables bitumineux chez Syncrude

Tony S. Dai et Martin Y.P. Fung

Syncrude Canada est une entreprise d'extraction minière et de transformation de sables bitumineux située au dépôt de sables bitumineux de l'Athabasca au nord-est de l'Alberta, Canada. Une estimation de 300 milliards de barils de pétrole est considérée comme récupérable pour ce dépôt. Le gouvernement albertain exige que les terres minières soient réhabilitées vers une utilisation acceptable avec une productivité égale ou meilleure à celle présente avant les opérations minières. Ce texte présente un aperçu de l'approche de réhabilitation couramment utilisée par Syncrude. Avant que l'enlèvement de la gangue soit réalisé, un échantillonnage intensif du sol est conduit pour déterminer la qualité et le volume du matériel de surface présent. Ces matériaux de sol sont alors utilisés pour recouvrir les résidus d'enrichissement avec un minimum de 70 cm et les amoncellements de résidus de la gangue avec au moins 100 cm de profondeur. Après que le recouvrement et la préparation du sol soient complétés, des semis d'arbres indigènes ayant poussés localement sont plantés. Quand la réhabilitation est terminée, la forme finale correspond à une topographie ondulante avec un drainage interne de l'eau du sol, et les propriétés du sol améliorées. On espère ainsi obtenir un écosystème au moins égal à celui d'avant les opérations minières en termes de productivité écologique. Les communautés végétales seront ainsi permanentes, autosuffisantes et ne nécessiteront pas d'entretien.

ACID-GENERATING MATERIALS

Caractérisation du filtrat produit par des sols contaminés aux sulfures

S. Leggett et D. Parkinson

Réhabiliter des sols qui sont lourdement contaminés par les sulfures est spécifique à une petite partie de l'industrie du pétrole et du gaz. Même si le problème n'est pas très répandu, il nécessite un effort de recherche individuel parce qu'il est différent des problèmes comme l'acidification des sols par les précipitations acides ou par la fertilisation des récoltes. L'effet de la contamination par les sulfures sur la qualité du filtrat produit par les sols aidera dans l'évaluation des risques potentiels pour l'environnement et la santé.

Les filtrats ont été amassés au début et à la fin d'un essai de croissance en serre à partir de pots contenant quatre niveaux de sulfures. Les niveaux de sulfures étaient de < 0.1% (contrôle), 4%, 9% et 14 %. Les traitements étaient les suivants: 1) application de $CaCO_3$ à un taux de trois fois celui des sulfures totaux détectés; 2) application de $CaCO_3$ (encore à un taux de trois fois celui des sulfures totaux détectés) et du fumier (40t/ha); 3) application de fumier (40t/ha); et 4) aucun traitement (contrôle). Les filtrats échantillonnés ont été filtrés et analysés pour le pH, la conductivité électrique, NO_3-N, NH_4-N, PO_4-P et SO_4-S. Des sous-échantillons sélectionnés ont été acidifiés et analysés pour Al, Mn et Fe solubles.

L'addition de fumier aux sols n'a pas produit de différences statistiques dans les paramètres de filtrage mesurés. Les filtrats produits pour les sols contaminés par les sulfures et sans chaux étaient fortement acides alors que les pH pour les filtrats des sols avec chaux et sulfures étaient neutres. Les valeurs de conductivité électrique étaient plus élevées dans les filtrats produits pour les sols contaminés par les sulfures et sans chaux. Les filtrats des sols avec chaux et sulfures étaient au moins dix fois plus bas que ceux qui n'avaient pas de chaux. Les filtrats produits pour les sols contaminés par les sulfures et sans chaux contenaient des niveaux élevés de NO_3, NH_4, PO_4, SO_4, aussi bien que des niveaux élevés d'Al, Fe et Mn solubles. Les filtrats produits par les sols avec chaux et sulfures contenaient des niveaux élevés de SO_4.

Les résultats obtenus par cette expérience indiquent qu'un délai pour neutraliser un sol lourdement contaminé avec des sulfures causerait un mouvement des métaux solubles vers le bas du profil de sol et peut aussi causer une perte des nutriments disponibles qui sont requis pour la revégétation.

Effets d'amendements phosphatés sur la production et la composition des éléments du maïs sur des sols miniers acides

D.K. Bhumbla et J.C. Sencindiver

Des expériences en serre ont été conduites pour évaluer la croissance et la composition chimique de trois récoltes de maïs sur des sols miniers avec ou sans chaux et amendés avec de l'argile phosphatée, de la potasse et du phosphate monocalcique. Les taux d'application de l'argile phosphatée et de la potasse étaient de 288 et 576 mg P/kg. L'argile phosphatée était également ajoutée à 1152 mg P/kg. Le phosphate monocalcique était ajouté à 50 mg P/kg, et un contôle n'avait aucun amendement phosphaté. Les productions de maïs étaient plus élevées sur les sols traités avec l'argile phosphatée que sur les sols avec la potasse ou le phosphate monocalcique. Les rendements n'étaient généralement pas meilleurs pour les hauts taux d'application qu'ils ne l'étaient pour le taux moyen d'argile phosphatée. L'argile phosphatée a amélioré l'assimilation des macronutriments par le maïs autant pour les sols avec ou sans chaux. Les concentrations de calcium et de phosphore étaient significativement plus élevées dans le tissu des plants ayant poussés sur les sols avec de l'argile phosphatée que pour les autres traitements. Les concentrations de fer et de manganèse dans les tissus diminuaient avec l'augmentation des niveaux d'amendement en phosphate.

The use of organic substances in the revegetation of acid mine tailings

Antoine Karam and Louis M. Azzaria

Revegetation of the East Sullivan mine tailings area in Val d'Or, Québec is probably the most suitable method of site stabilization. However, the tailings have undesireable characteristics for germination and growth of plants, including low organic content, low pH, major nutrient deficiencies and high levels of iron sulphides.

The paper discusses results obtained in greenhouse and laboratory tests on revegetation of East Sullivan mine tailings. Experiments examined the effect of organic substances (sewage sludge and sawdust) on: 1) growth of corn, and 2) chemical characteristics of tailings and leachate.

Considérations sur le design du traitement passif du drainage minier acide

Thomas R. Wildeman, Leslie S. Laudon et E. A. Howard

Des considérations et des recommandations sur le design de systèmes de bassin humides à utiliser dans des environnemnts montagneux difficiles sont données. La base des recommandations est un site de recherche pour le traitement passif du drainage acide qui a été dessiné et construit à "The Big Five Tunnel", un des nombreux sites du CERCLA dans le district minier de "Idaho Springs-Central City" au Colorado. Les principaux traits aussi bien que les problèmes rencontrés durant la construction et le début de la démonstration du système seront présentés. Alors, en se basant sur l'expérience de ce site et sur l'analyse d'autres sites, des suggestions et des idées sur les phases suivantes seront présentées: les plans préliminaires projetés, les exigences pour les surfaces de bassins humides, la configuration du bassin, les méthodes sur la distribution du drainage de la mine vers le bassin, le choix et la construction du substrat et la sélection et la plantation de la végétation.

Mesures d'ingénierie écologique développées pour des résidus de cuivre et de zinc générant de l'acidité au nord de l'Ontario

M. Kalin et G. Mallory

Un concentrateur de cuivre et de zinc localisé dans la région de Red Lake au nord de l'Ontario a été fermé en 1981. Sur une superficie de 25 hectares, on retrouve 760 000 tonnes de résidus d'enrichissement à l'intérieur de bassins. Les résidus contiennent environ 41 % de pyrite et 4.1 % de pyrrhotite. Le site minier de 75 hectares, incluant le site de la ville et le moulin, est entouré par des lacs de pêche sportive du bassin de drainage de la rivière English.

Les procédures de réaffectation incluent les étapes qui assureront une qualité de l'eau de surface acceptable à long terme. Comme l'ingénierie écologique semble adéquate pour fournir une telle solution à des résidus générant de l'acidité sur le site, les efforts sont dirigés vers le développement de mesures employant cette approche.

L'eau souterraine acide générée par les résidus était interceptée par des fossés, alors que l'eau de surface était dirigée vers des bassins de neutralisation sur le site. Premièrement, la capacité de neutralisation biologique dans les deux bassins d'eau majeurs a été améliorée par les conditions requises pour la prolifération des agents biologiques de neutralisation. Ceux-çi sont des algues complexes dominées par Achnanthes et Mougeotia spp. dans les eaux acides (pH 3.5), et Navicula et Ocillatoria spp. dans les eaux près de la neutralité (pH 6.5). En second lieu, une mousse aquatique tolérante à l'acidité a été introduite dans le système de neutralisation. La population de mousse forme un tapis sur la surface des sédiments, prévenant le contact de l'oxygène avec cette dernière et fournissant ainsi un "accumulateur" pour les métaux lourds enlevés par les agents neutralisants. Dans les bassins peu profonds et légèrement acides, des îlots de quenouilles ont été construits pour le même usage.

Une description de ce système d'ingénierie écologique et sa performance pour la première année seront données dans ce texte.

Purification de l'eau résiduelle d'une mine de Pb/Zn par l'utilisation d'hydrophytes

Chongyu Lan, Guizhu Chen, Liuchun Li et M.H. Wong

C'est une pratique commune dans plusieurs pays d'utiliser des hydrophytes pour traiter les effluents industriels et municipaux. Ce texte décrit l'utilisation d'un bassin de purification avec Typha latifolia Linn (Typhaceaes) comme espèces dominantes, pour traiter l'eau résiduelle d'une mine de Pb/Zn à Shaoguan, dans la province de Guangdong en Chine.

Un survol préliminaire de la région minière a été fait en 1983 et il a été noté que Typha latifolia poussait très bien dans les endroits affectés par l'eau résiduelle émise par la mine. Un bassin de purification a été construit subséquemment par la compagnie minière pour traiter les eaux résiduelles en englobant la surface dominée par T. latifolia. Des débris rocheux et du gravier ont été utilisés pour construire le barrage. Le bassin a une capacité de 87,500 m^2 avec une capacité de traitement de 29,927 tonnes/jour.

Les eaux résiduelles non traitées avant d'entrer dans le bassin contenaient des niveaux plutôt élevés de solides en suspension (4635 mg/l), une demande en oxygène (14.5 mg/l) aussi bien que du plomb (1.6 mg/l) et du zinc (1.9 mg/l). Après avoir passé au travers du bassin de purification, la qualité de l'eau s'est améliorée substantiellement, avec les solides en suspension réduits de 99%, la demande en oxygène de 55%, le plomb de 87% et le zinc de 81%.

Les résultats de l'analyse des tissus des plantes indiquaient que T. latifolia a une habileté intéressante pour assimiler le plomb et le zinc, spécialement dans la zone racinaire. La zone racinaire contenait 717 ug/g Pb et 433 ug/g Zn, qui étaient 14 et 4.4 fois plus élevés que sa contrepartie poussant dans la région non contaminée.

Une surveillance écologique conduite en 1986 a indiqué également qu'il y avait plusieurs espèces d'algues et de poissons florissant dans le bassin, habituellement avec une densité plus élevée dans les endroits contenant des concentrations moindres en métaux lourds dans l'eau.

RECLAMATION RESEARCH REPORTS

**	1.	RRTAC 80-3:	The Role of Organic Compounds in Salinization of Plains Coal Mining Sites. N.S.C. Cameron et al. 46 pp.
		DESCRIPTION:	This is a literature review of the chemistry of sodic mine spoil and the changes expected to occur in groundwater.
**	2.	RRTAC 80-4:	Proceedings: Workshop on Reconstruction of Forest Soils in Reclamation. P.F. Ziemkiewicz, S.K. Takyi, and H.F. Regier. 160 pp.
		DESCRIPTION:	Experts in the field of forestry and forest soils report on research relevant to forest soil reconstruction and discuss the most effective means of restoring forestry capability of mined lands.
N/A	3.	RRTAC 80-5:	Manual of Plant Species Suitability for Reclamation in Alberta. L.E. Watson, R.W. Parker, and D.F. Polster. 2 vols, 541 pp.
		DESCRIPTION:	Forty-three grass, fourteen forb, and thirty-four shrub and tree species are assessed in terms of their suitability for use in reclamation. Range maps, growth habit, propagation, tolerance, and availability information are provided.
*	4.	RRTAC 81-2:	1980 Survey of Reclamation Activities in Alberta. D.G. Walker and R.L. Rothwell. 76 pp.
		DESCRIPTION:	This survey is an update of a report prepared in 1976 on reclamation activities in Alberta, and includes research and operational reclamation, locations, personnel, etc.
**	5.	RRTAC 81-3:	Proceedings: Workshop on Coal Ash and Reclamation. P.F. Ziemkiewicz, R. Stein, R. Leitch, and G. Lutwick. 253 pp.
		DESCRIPTION:	Presents nine technical papers on the chemical, physical, and engineering properties of Alberta fly and bottom ashes, revegetation of ash disposal sites, and use of ash as a soil amendment. Workshop discussions and summaries are also included.

N/A 6. RRTAC 82-1: Land Surface Reclamation: An International Bibliography. H.P. Sims and C.B. Powter. 2 vols, 292 pp.

DESCRIPTION: Literature to 1980 pertinent to reclamation in Alberta is listed in Vol. 1 and is also on the University of Alberta computing system (in a SPIRES database called RECLAIM). Vol. 2 comprises the keyword index and computer access manual.

N/A 7. RRTAC 82-2: A Bibliography of Baseline Studies in Alberta: Soils, Geology, Hydrology, and Groundwater. C.B. Powter and H.P. Sims. 97 pp.

DESCRIPTION: This bibliography provides baseline information for persons involved in reclamation research or in the preparation of environmental impact assessments. Materials, up to date as of December 1981, are available in the Alberta Environment Library.

N/A 8. RRTAC 83-1: Soil Reconstruction Design for Reclamation of Oil Sand Tailings. Monenco Consultants Ltd. 185 pp.

DESCRIPTION: Volumes of peat and clay required to amend oil sand tailings were estimated based on existing literature. Separate soil prescriptions were made for spruce, jack pine, and herbaceous cover types. The estimates form the basis of field trials.

N/A 9. RRTAC 83-3: Evaluation of Pipeline Reclamation Practices on Agricultural Lands in Alberta. Hardy Associates (1978) Ltd. 205 pp.

DESCRIPTION: Available information on pipeline reclamation practices was reviewed. A field survey was then conducted to determine the effects of pipe size, age, soil type, construction method, etc. on resulting crop production.

** 10. RRTAC 83-4: Proceedings: Effects of Coal Mining on Eastern Slopes Hydrology. P.F. Ziemkiewicz. 123 pp.

DESCRIPTION: Technical papers are presented dealing with the impacts of mining on mountain watersheds, their flow characteristics, and resulting water quality. Mitigative measures and priorities were also discussed.

N/A	11.	RRTAC 83-5:	Woody Plant Establishment and Management for Oil Sands Mine Reclamation. Techman Engineering Ltd. 124 pp.
		DESCRIPTION:	This is a review and analysis of information on planting stock quality, rearing techniques, site preparation, planting, and procedures necessary to ensure survival of trees and shrubs in oil sand reclamation.
***	12.	RRTAC 84-1:	Land Surface Reclamation: A Review of the International Literature. H.P. Sims, C.B. Powter, and J.A. Campbell. 2 vols, 1549 pp.
		DESCRIPTION:	Nearly all topics of interest to reclamationists including mining methods, soil amendments, revegetation, propagation and toxic materials are reviewed in light of the international literature.
**	13.	RRTAC 84-2:	Propagation Study: Use of Trees and Shrubs for Oil Sand Reclamation. Techman Engineering Ltd. 58 pp.
		DESCRIPTION:	This report evaluates and summarizes all available published and unpublished information on large-scale propagation methods for shrubs and trees to be used in oil sand reclamation.
*	14.	RRTAC 84-3:	Reclamation Research Annual Report - 1983. P.F. Ziemkiewicz. 42 pp.
		DESCRIPTION:	This report details the Reclamation Research Program indicating priorities, descriptions of each research project, researchers, results, and expenditures.
**	15.	RRTAC 84-4:	Soil Microbiology in Land Reclamation. D. Parkinson, R.M. Danielson, C. Griffiths, S. Visser, and J.C. Zak. 2 vols, 676 pp.
		DESCRIPTION:	This is a collection of five reports dealing with re-establishment of fungal decomposers and mycorrhizal symbionts in various amended spoil types.
**	16.	RRTAC 85-1:	Proceedings: Revegetation Methods for Alberta's Mountains and Foothills. P.F. Ziemkiewicz. 416 pp.
		DESCRIPTION:	Results of long-term experiments and field experience on species selection, fertilization, reforestation, topsoiling, shrub propagation and establishment are presented.

*	17. RRTAC 85-2:	Reclamation Research Annual Report - 1984. P.F. Ziemkiewicz. 29 pp.
	DESCRIPTION:	This report details the Reclamation Research Program indicating priorities, descriptions of each research project, researchers, results, and expenditures.
**	18. RRTAC 86-1:	A Critical Analysis of Settling Pond Design and Alternative Technologies. A. Somani. 372 pp.
	DESCRIPTION:	The report examines the critical issue of settling pond design, and sizing and alternative technologies. The study was co-funded with The Coal Association of Canada.
**	19. RRTAC 86-2:	Characterization and Variability of Soil Reconstructed after Surface Mining in Central Alberta. T.M. Macyk. 146 pp.
	DESCRIPTION:	Reconstructed soils representing different materials handling and replacement techniques were characterized, and variability in chemical and physical properties was assessed. The data obtained indicate that reconstructed soil properties are determined largely by parent material characteristics and further tempered by materials handling procedures. Mining tends to create a relatively homogeneous soil landscape in contrast to the mixture of diverse soils found before mining.
*	20. RRTAC 86-3:	Generalized Procedures for Assessing Post-Mining Groundwater Supply Potential in the Plains of Alberta - Plains Hydrology and Reclamation Project. M.R. Trudell and S.R. Moran. 30 pp.
	DESCRIPTION:	In the Plains region of Alberta, the surface mining of coal generally occurs in rural, agricultural areas in which domestic water supply requirements are met almost entirely by groundwater. Consequently, an important aspect of the capability of reclaimed lands to satisfy the needs of a residential component is the post-mining availability of groundwater. This report proposes a sequence of steps or procedures to identify and characterize potential post-mining aquifers.

** 21. RRTAC 86-4: Geology of the Battle River Site: Plains Hydrology and Reclamation Project. A. Maslowski-Schutze, R. Li, M. Fenton and S.R. Moran. 86 pp.

DESCRIPTION: This report summarizes the geological setting of the Battle River study site. It is designed to provide a general understanding of geological conditions adequate to establish a framework for hydrogeological and general reclamation studies. The report is not intended to be a detailed synthesis such as would be required for mine planning purposes.

** 22. RRTAC 86-5: Chemical and Mineralogical Properties of Overburden: Plains Hydrology and Reclamation Project. A. Maslowski-Schutze. 71 pp.

DESCRIPTION: This report describes the physical and mineralogical properties of overburden materials in an effort to identify individual beds within the bedrock overburden that might be significantly different in terms of reclamation potential.

* 23. RRTAC 86-6: Post-Mining Groundwater Supply at the Battle River Site: Plains Hydrology and Reclamation Project. M.R. Trudell, G.J. Sterenberg and S.R. Moran. 49 pp.

DESCRIPTION: The report deals with the availability of water supply in or beneath cast overburden to support post-mining land use, including both quantity and quality considerations. The study area is in the Battle River Mining area in east-central Alberta

* 24. RRTAC 86-7: Post-Mining Groundwater Supply at the Highvale Site: Plains Hydrology and Reclamation Project. M.R. Trudell. 25 pp.

DESCRIPTION: This report evaluates the availability of water supply in or beneath cast overburden to support post-mining land use, including both quantity and quality considerations. The study area is the Highvale mining area in west-central Alberta.

* 25. RRTAC 86-8: Reclamation Research Annual Report - 1985. P.F. Ziemkiewicz. 54 pp.

DESCRIPTION: This report details the Reclamation Research Program indicating priorities, descriptions of each research project, researchers, results, and expenditures.

** 26. RRTAC 86-9: Wildlife Habitat Requirements and Reclamation Techniques for the Mountains and Foothills of Alberta. J.E. Green, R.E. Salter and D.G. Walker. 285 pp.

DESCRIPTION: This report presents a review of relevant North American literature on wildlife habitats in mountain and foothills biomes, reclamation techniques, potential problems in wildlife habitat reclamation, and potential habitat assessment methodologies. Four biomes (Alpine, Subalpine, Montane, and Boreal Uplands) and 10 key wildlife species (snowshoe hare, beaver, muskrat, elk, moose, caribou, mountain goat, bighorn sheep, spruce grouse, and white-tailed ptarmigan) are discussed. The study was co-funded with The Coal Association of Canada.

N/A 27. RRTAC 87-1: Disposal of Drilling Wastes. L.A. Leskiw, E. Reinl-Dwyer, T.L. Dabrowski, B.J. Rutherford and H. Hamilton. 210 pp.

DESCRIPTION: Current drilling waste disposal practices are reviewed and criteria in Alberta guidelines are assessed. The report also identifies research needs and indicates mitigation measures. A manual provides a decision-making flowchart to assist in selecting methods of environmentally safe waste disposal.

** 28. RRTAC 87-2: Minesoil and Landscape Reclamation of the Coal Mines in Alberta's Mountains and Foothills. A.W. Fedkenheuer, L.J. Knapik and D.G. Walker. 174 pp.

DESCRIPTION: This report reviews current reclamation practices with regard to site and soil reconstruction and re-establishment of biological productivity. It also identifies research needs in the Mountain-Foothills area. The study was co-funded with The Coal Association of Canada.

** 29. RRTAC 87-3: Gel and Saline Drilling Wastes in Alberta: Workshop Proceedings. D.A. Lloyd (compiler). 218 pp.

DESCRIPTION: Technical papers were presented which describe: mud systems used and their purpose; industrial constraints; government regulations, procedures and concerns; environmental considerations in waste disposal; and toxic constituents of drilling wastes. Answers to a questionnaire distributed to participants are included in an appendix.

* 30. RRTAC 87-4: Reclamation Research Annual Report - 1986. 50 pp.

DESCRIPTION: This report details the Reclamation Research Program indicating priorities, descriptions of each research project, researchers, results, and expenditures.

* 31. RRTAC 87-5: Review of the Scientific Basis of Water Quality Criteria for the East Slope Foothills of Alberta. Beak Associates Consulting Ltd. 46 pp.

DESCRIPTION: The report reviews existing Alberta guidelines to assess the quality of water drained from coal mine sites in the East Slope Foothills of Alberta. World literature was reviewed within the context of the East Slopes environment and current mining operations. The ability of coal mine operators to meet the various guidelines is discussed. The study was co-funded with The Coal Association of Canada.

** 32. RRTAC 87-6: Assessing Design Flows and Sediment Discharge on the Eastern Slopes. Hydrocon Engineering (Continental) Ltd. and Monenco Consultants Ltd. 97 pp.

DESCRIPTION: The report provides an evaluation of current methodologies used to determine sediment yields due to rainfall events in well-defined areas. Models are available in Alberta to evaluate water and sediment discharge in a post-mining situation. SEDIMOT II (Sedimentology Disturbed Modelling Techniques) is a single storm model that was developed specifically for the design of sediment control structures in watersheds disturbed by surface mining and is well suited to Alberta conditions. The study was co-funded with The Coal Association of Canada.

* 33. RRTAC 87-7: The Use of Bottom Ash as an Amendment to Sodic Spoil. S. Fullerton. 83 pp.

DESCRIPTION: The report details the use of bottom ash as an amendment to sodic coal mine spoil. Several rates and methods of application of bottom ash to sodic spoil were tested to determine which was the best at reducing the effects of excess sodium and promoting crop growth. Field trials were set up near the Vesta mine in East Central Alberta using ash readily available from a nearby coal-fired thermal generating station. The research indicated that bottom ash incorporated to a depth of 30 cm using a subsoiler provided the best results.

* 34. RRTAC 87-8: Waste Dump Design for Erosion Control. R.G. Chopiuk and S.E. Thornton. 45 pp.

DESCRIPTION: This report describes a study to evaluate the potential influence of erosion from reclaimed waste dumps on downslope environments such as streams and rivers. Sites were selected from coal mines in Alberta's mountains and foothills, and included resloped dumps of different configurations and ages, and having different vegetation covers. The study concluded that the average annual amount of surface erosion is minimal. As expected, erosion was greatest on slopes which were newly regraded. Slopes with dense grass cover showed no signs of erosion. Generally, the amount of erosion decreased with time, as a result of initial loss of fine particles, the formation of a weathered surface, and increased vegetative cover.

** 35. RRTAC 87-9: Hydrogeology and Groundwater Chemistry of the Battle River Mining Areas. M.R. Trudell, R.L. Faught and S.R. Moran. 97 pp.

DESCRIPTION: This report describes the premining geologic conditions in the Battle River coal mining area including the geology as well as the groundwater flow patterns, and the groundwater quality of a sequence of several water-bearing formations extending from the surface to a depth of about 100 metres.

** 36. RRTAC 87-10: Soil Survey of the Plains Hydrology and Reclamation Project - Battle River Project Area. T.M. Macyk and A.H. MacLean. 62 pp. plus 8 maps.

DESCRIPTION: The report evaluates the capability of post-mining landscapes and assesses the changes in capability as a result of mining, in the Battle River mining area. Detailed soils information is provided in the report for lands adjacent to areas already mined as well as for lands that are destined to be mined. Characterization of the reconstructed soils in the reclaimed areas is also provided. Data were collected from 1979 to 1985. Eight maps supplement the report.

** 37. RRTAC 87-11: Geology of the Highvale Study Site: Plains Hydrology and Reclamation Project. A. Maslowski-Schutze. 78 pp.

DESCRIPTION: The report is one of a series that describes the geology, soils and groundwater conditions at the Highvale Coal Mine study site. The purpose of the study was to establish a summary of site geology to a level of detail necessary to provide a framework for studies of hydrogeology and reclamation.

** 38. RRTAC 87-12: Premining Groundwater Conditions at the Highvale Site. M.R. Trudell and R. Faught. 83 pp.

DESCRIPTION: This report presents a detailed discussion of the premining flow patterns, hydraulic properties, and isotopic and hydrochemical characteristics of five layers within the Paskapoo Geological Formation, the underlying sandstone beds of the Upper Horseshoe Canyon Formation, and the surficial glacial drift.

* 39. RRTAC 87-13: An Agricultural Capability Rating System for Reconstructed Soils. T.M. Macyk. 27 pp.

DESCRIPTION: This report provides the rationale and a system for assessing the agricultural capability of reconstructed soils. Data on the properties of the soils used in this report are provided in RRTAC 86-2.

** 40. RRTAC 88-1: A Proposed Evaluation System for Wildlife Habitat Reclamation in the Mountains and Foothills Biomes of Alberta: Proposed Methodology and Assessment Handbook. T.R. Eccles, R.E. Salter and J.E. Green. 101 pp. plus appendix.

DESCRIPTION: The report focuses on the development of guidelines and procedures for the assessment of reclaimed wildlife habitat in the Mountains and Foothills regions of Alberta. The technical section provides background documentation including a discussion of reclamation planning, a listing of reclamation habitats and associated key wildlife species, conditions required for development, recommended revegetation species, suitable reclamation techniques, a description of the recommended assessment techniques and a glossary of basic terminology. The assessment handbook section contains basic information necessary for evaluating wildlife habitat reclamation, including assessment scoresheets for 15 different reclamation habitats, standard methodologies for measuring habitat variables used as assessment criteria, and minimum requirements for certification. This handbook is intended as a field manual that could potentially be used by site operators and reclamation officers. The study was co-funded with The Coal Association of Canada.

** 41. RRTAC 88-2: Plains Hydrology and Reclamation Project: Spoil Groundwater Chemistry and its Impacts on Surface Water. M.R. Trudell (compiler). 135 pp.

DESCRIPTION: Two reports comprise this volume. The first "Chemistry of Groundwater in Mine Spoil, Central Alberta," describes the chemical make-up of spoil groundwater at four mines in the Plains of Alberta. It explains the nature and magnitude of changes in groundwater chemistry following mining and reclamation. The second report, "Impacts of Surface Mining on Chemical Quality of Streams in the Battle River Mining Area," describes the chemical quality of water in streams in the Battle River mining area, and the potential impact of groundwater discharge from surface mines on these streams.

** 42. RRTAC 88-3: Revegetation of Oil Sands Tailings: Growth Improvement of Silver-berry and Buffalo-berry by Inoculation with Mycorrhizal Fungi and N_2-Fixing Bacteria. S. Visser and R.M. Danielson. 98 pp.

DESCRIPTION: The report provides results of a study: (1) To determine the mycorrhizal affinities of various actinorrhizal shrubs in the Fort McMurray, Alberta region; (2) To establish a basis for justifying symbiont inoculation of buffalo-berry and silver-berry; (3) To develop a growing regime for the greenhouse production of mycorrhizal, nodulated silver-berry and buffalo-berry; and, (4) To conduct a field trial on reconstructed soil on the Syncrude Canada Limited oil sands site to critically evaluate the growth performance of inoculated silver-berry and buffalo-berry as compared with their uninoculated counterparts.

** 43. RRTAC 88-4: Plains Hydrology and Reclamation Project: Investigation of the Settlement Behaviour of Mine Backfill. D.R. Pauls (compiler). 135 pp.

DESCRIPTION: This three part volume covers the laboratory assessment of the potential for subsidence in reclaimed landscapes. The first report in this volume, "Simulation of Mine Spoil Subsidence by Consolidation Tests," covers laboratory simulations of the subsidence process particularly as it is influenced by resaturation of mine spoil. The second report, "Water Sensitivity of Smectitic Overburden: Plains Region of Alberta," describes a series of laboratory tests to determine the behaviour of overburden materials when brought into contact with water. The report entitled "Classification System for Transitional Materials: Plains Region of Alberta," describes a lithological classification system developed to address the characteristics of the smectite rich, clayey transition materials that make up the overburden in the Plains of Alberta.

** 44. RRTAC 88-5: Ectomycorrhizae of Jack Pine and Green Alder: Assessment of the Need for Inoculation, Development of Inoculation Techniques and Outplanting Trials on Oil Sand Tailings. R.H. Danielson and S. Visser. 177 pp.

DESCRIPTION: The overall objective of this research was to characterize the mycorrhizal status of Jack Pine and Green Alder which are prime candidates as reclamation species for oil sand tailings and to determine the potential benefits of mycorrhizae on plant performance. This entailed determining the symbiont status of container-grown nursery stock and the quantity and quality of inoculum in reconstructed soils, developing inoculation techniques and finally, performance testing in an actual reclamation setting.

* 45. RRTAC 88-6: Reclamation Research Annual Report - 1987. Reclamation Research Technical Advisory Committee. 67 pp.

DESCRIPTION: This annual report describes the expenditure of $500,000.00 of Alberta Heritage Savings Trust Fund monies on research under the Land Reclamation Program. The report outlines the objectives and research strategies of the four program areas, and describes the projects funded under each program.

* 46. RRTAC 88-7: Baseline Growth Performance Levels and Assessment Procedure for Commercial Tree Species in Alberta's Mountains and Foothills. W.R. Dempster and Associates Ltd. 66 pp.

DESCRIPTION: Data on juvenile height development of lodgepole pine and white spruce from cut-over or burned sites in the Eastern Slopes of Alberta were used to define reasonable expectations of early growth performance as a basis for evaluating the success of reforestation following coal mining. Equations were developed predicting total seedling height and current annual height increment as a function of age and elevation. Procedures are described for applying the equations, with further adjustments for drainage class and aspect, to develop local growth performance against these expectations. The study was co-funded with The Coal Association of Canada.

** 47. RRTAC 88-8: Alberta Forest Service Watershed Management Field and Laboratory Methods. A.M.K. Nip and R.A. Hursey, Alberta Forest Service. 4 Sections, various pagings.

DESCRIPTION: Disturbances such as coal mines in the Eastern Slopes of Alberta have the potential for affecting watershed quality during and following mining. The collection of hydrometric, water quality and hydrometeorologic information is a complex task. A variety of instruments and measurement methods are required to produce a record of hydrologic inputs and outputs for a watershed basin. There is a growing awareness and recognition that standardization of data acquisition methods is required to ensure data comparability, and to allow comparison of data analyses. The purpose of this manual is to assist those involved in the field of data acquisition by outlining methods, practices and instruments which are reliable and recognized by the International Organization for Standardization.

** 48. RRTAC 88-9: Computer Analysis of the Factors Influencing Groundwater Flow and Mass Transport in a System Disturbed by Strip Mining. F.W. Schwartz and A.S. Crowe, SIMCO Groundwater Research Ltd. 78 pp.

DESCRIPTION: Work presented in this report demonstrates how a groundwater flow model can be used to study a variety of mining-related problems such as declining water levels in areas around the mine as a result of dewatering, and the development of high water tables in spoil once resaturation is complete. This report investigates the role of various hydrogeological parameters that influence the magnitude, timing, and extent of water level changes during and following mining at the regional scale. The modelling approach described here represents a major advance on existing work.

* 49. RRTAC 88-10: Review of Literature Related to Clay Liners for Sump Disposal of Drilling Wastes. D.R. Pauls, S.R. Moran and T. Macyk, 1988. 61 pp.

DESCRIPTION: The report reviews and analyses the effectiveness of geological containment of drilling waste in sumps. Of particular importance was the determination of changes in properties of clay materials as a result of contact with highly saline brines containing various organic chemicals.

** 50. RRTAC 88-11: Highvale Soil Reconstruction Project: Five Year Summary. D.N. Graveland, T.A. Oddie, A.E. Osborne and L.A. Panek, Monenco Consultants Limited. 104 pp.

DESCRIPTION: This report provides details of a five year study to determine a suitable thickness of subsoil to replace over minespoil in the Highvale plains coal mine area to ensure return of agricultural capability. The study also examined the effect of slope and aspect on agricultural capability. This study was funded and managed with industry assistance.

* 51. RRTAC 88-12: A Review of the International Literature on Mine Spoil Subsidence. J.D. Scott, G. Zinter, D.R. Pauls and M.B. Dusseault, University of Alberta and University of Waterloo. 36 pp.

DESCRIPTION: The report reviews available engineering literature relative to subsidence of reclaimed mine spoil. The report covers methods for site investigation, field monitoring programs and laboratory programs, mechanisms of settlement, and remedial measures. Abstracts for 46 reports are provided.

* 52. RRTAC 89-1: Reclamation Research Annual Report - 1988. Reclamation Research Technical Advisory Committee. 73 pp.

DESCRIPTION: This annual report describes the expenditure of $280,000.00 of Alberta Heritage Savings Trust Fund monies on research under the Land Reclamation Program. The report outlines the objectives and research strategies of the four program areas, and describes the projects funded under each program.

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